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THESIS

MODELING AND ANALYSIS OF HUMAN ERROR IN NAVAL AVIATION MAINTENANCE MISHAPS

by

Ashley D. Fry

June 2000

Thesis Advisor:	John K. Schmidt
Second Reader:	Samuel E. Buttrey

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This study investigates human error associated with 599 Naval Aviation maintenance-related mishaps (MRMs) in Fiscal Years 90-99. The Human Factors Analysis and Classification System Maintenance Extension (HFACS-ME) taxonomy was utilized to classify contributory human errors within a robust theoretical framework. Variable Poisson process models are developed to predict MRMs and relationships between the error dimensions are investigated. The results of this study show that the HFACS-ME taxonomy provides an adequate framework for the classification of MRM causal factors; that variable Poisson process models are suitable for predicting future mishaps, and that there are significant relationships between selected causal dimensions; sufficient to warrant further investigation. These results provide information regarding the predicted impact of MRMs on future operational readiness and mission capability. Through being aware of these aspects, decision-makers are armed with the knowledge to make better decisions concerning the preservation and allocation of the resources at their disposal.

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ANALYSIS AND MODELING OF HUMAN ERROR IN NAVAL AVIATION MAINTENANCE MISHAPS

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ABSTRACT

This study investigates human error associated with 599 Naval Aviation maintenance-related mishaps (MRMs) in Fiscal Years 90-99. The Human Factors Analysis and Classification System Maintenance Extension (HFACS-ME) taxonomy was utilized to classify contributory human errors within a robust theoretical framework. Variable Poisson process models are developed to predict MRMs and relationships between the error dimensions are investigated. The results of this study show that the HFACS-ME taxonomy provides an adequate framework for the classification of MRM causal factors; that variable Poisson process models are suitable for predicting future mishaps; and that there are significant relationships between selected causal dimensions, sufficient to warrant further investigation. These results provide information regarding the predicted impact of MRMs on future operational readiness and mission capability. Through being aware of these aspects, decision-makers are armed with the knowledge to make better decisions concerning the preservation and allocation of the resources at their disposal.

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TABLE OF CONTENTS

LIST OF FIGURES

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LIST OF TABLES

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LIST OF ACRONYMS

AGM	Aircraft-Ground Mishap
AMB	Aircraft Mishap Board
DOD	Department of Defense
DON	Department of the Navy
FM	Flight Mishap
FRM	Flight-Related Mishap
FY	Fiscal Year
HFACS-ME	Human Factors Analysis and Classification System Maintenance Extension
MIR	Mishap Investigation Report
MRM	Maintenance-Related Mishap
NASC	Naval Air Systems Command
NSC	Naval Safety Center
NPS	Naval Postgraduate School

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EXECUTIVE SUMMARY

Budgetary constraints imposed upon the US military are particularly burdensome as they are being imposed while demands for aspects such as mission capability, adequate training and operational readiness are being maintained. Throughout the military, leaders are looking at their operations and critically evaluating the applicability, cost, utility, and value of their functions. A closer self-examination by Naval Aviation has revealed potential asset preservation and associated cost savings through the reduction of avoidable human errors that contribute to mishaps.

Advances in technology and reliability, combined with numerous intervention strategies, have effectively targeted materiel reliability to the extent that the number of mishaps related to mechanical failure has declined at a greater rate than those tied to human error. Nearly all Naval Aviation mishaps involve some form of human error, predominately aircrew or maintainer error, yet the reporting system does not support the systematic inclusion of data at the time of the investigation that pertains to a theoretical human error framework. Many studies offer theoretical models that focus on aircrew-related error, leaving maintenance as the much maligned "stepchild," often criticized, but seldom offered assistance in addressing its failings. In an attempt to address this, a "Maintenance Extension" for the Naval Safety Center's Human Factors Analysis and Classification System (HFACS-ME) taxonomy was developed. The HFACS-ME model, which focuses on causation factors particular to the maintenance environment, is based upon current organizational and psychological theories of human error. It views a maintainer's performance as being influenced by a series of latent conditions

(supervisory, maintainer, and working conditions) that can lead to an unsafe maintainer act, which in turn can lead to a mishap, ground damage, injury, or unsafe maintenance condition.

The purpose of this study is to investigate human errors in Naval Aviation maintenance-related mishaps (MRMs) by conducting a human factors analysis to predict the occurrence of future MRMs and to analyze trends in causal factors. There are two objectives: The first is to validate previously developed models that attempted to predict future mishaps as a stochastic model with a variable Poisson arrival process. Secondly, a data analysis will be conducted on the mishap data of the past ten years to determine if there are significant trends or relationships within the factors attributed to MRMs.

The results of this study show that the HFACS-ME taxonomy provides an adequate framework for the classification of MRM causal factors. Additionally, through the validation of the previously developed stochastic models, it was confirmed that the variable Poisson process model provides a satisfactorily robust, yet straightforward model for predicting the number of future mishaps. The trend analysis of the causal factors of MRMs revealed that there is a significant relationship between the causal dimensions of Squadron Supervisory Conditions (SQN) and Maintainer Violation (VIO), enough to warrant the suggestion that the correlation of these aspects be further investigated.

ACKNOWLEDGEMENTS

The author would like to acknowledge and express gratitude to both Commander John Schmidt and Professor Samuel Buttrey for their tremendous assistance, prudent direction, sincere dedication, and good humor throughout the conduct of this study. Particular thanks is also conveyed to "Doc" Schmidt for his mentoring during the past year, as well as for his personal and career guidance. Thank you for believing in me.

Appreciation and gratitude is expressed to my parents, Annette and Arthur Fry. Regardless of the challenges that I have faced in life, I have always received their love, encouragement and support, this being no exception. I am eternally grateful, for without them I would not have achieved nearly as much. Acknowledgement and gratitude is expressed also to Joy Helgerson for her assistance, support and patience during the latter part of my time in the US.

Acknowledgement and gratitude is expressed to the members of the faculty who displayed a genuine concern for my education. A final word of thanks goes to my fellow classmates who not only made my time in the US a truly enjoyable experience, but who also fostered a tremendous team spirit as we met the task of being proficient in our studies.

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I. INTRODUCTION

A. OVERVIEW

The United States has been at the forefront of a worldwide economic boom that has seen unparalleled prosperity in the last decade of the 20th century (Svensson, 1999). Despite this, US Government agencies are still finding themselves subject to sustained requirements to become efficient business-like entities. The US military is not exempt from these efficiency measures and accordingly, budgetary constraints are still very much in evidence, causing military decision-makers to search for potential asset preservation and associated cost savings (Lockhardt, 1997). These budgetary constraints are particularly burdensome as they are being imposed while demands for aspects such as adequate training and operational readiness are being maintained. Throughout the military, managers are looking at their operations and critically evaluating the applicability, cost, utility and value of their functions. The *low-hanging fruit* — the areas with the most tangible benefits — has long since been harvested and attention is now being focused on less easily defined and more intangible costs (Lauber, 2000).

In accordance with operational and budgetary demands, a closer self-examination by Naval Aviation has revealed potential asset preservation and associated cost savings through the reduction of avoidable human errors that contribute to mishaps (Nutwell & Sherman, 1997). To achieve this, Naval Aviation must identify the types of human error associated with mishaps, and then implement intervention programs and strategies aimed at reducing the causes of these errors (Shappell & Weigmann, 1997). This study will take another step toward that goal. It will identify particular categories of human error

associated with past mishaps and then develop mathematical models and investigate potential trends relating to these errors. This evaluation should provide the most likely impact a program of focused error reduction might have.

B. BACKGROUND

Compared to other means of transportation, aviation is relatively new – it has yet to reach its 100th anniversary. Another factor that sets it apart from other forms of transportation is in the different culture that it has developed. Aviation has fostered an extensive safety-oriented culture where the checks and balances in place far outweigh those in most similar transport-related industries (Johnson, 1993). Additionally, the extent to which aviation accidents are investigated is far greater than those of ground-based transportation, with the findings of these accident investigations typically focused on preventing similar mishaps. In the past, most mishap reduction efforts have been directed at reducing or eliminating mechanical failure (Weigmann & Shappell, 1997). These efforts have made air travel – the safest mode of transportation (in terms of fatalities per passenger mile) – even safer (Parker, 1992).

In the past twenty years advances in technology and reliability, combined with numerous intervention strategies, have contributed to an overall decline in the number of Naval Aviation Class A flight mishaps (Dirren, 2000) – the most serious accident category (see Figure 1). The majority of strategies effectively targeted materiel reliability to the extent that the number of accidents related to mechanical failure has declined at a far greater rate than those pertaining to human error (Reason, 1997a). Accordingly, the proportion of mishaps attributable to human error has increased and become a more

visible target for reduction strategies. The National Transportation Safety Board has taken this fact seriously, and in conjunction with the Federal Aviation Administration, has implemented many programs to address human error (Goglia, 2000). The majority of these programs are comparatively in their infancy and address aspects such as personnel attitudes and interpersonal communication.

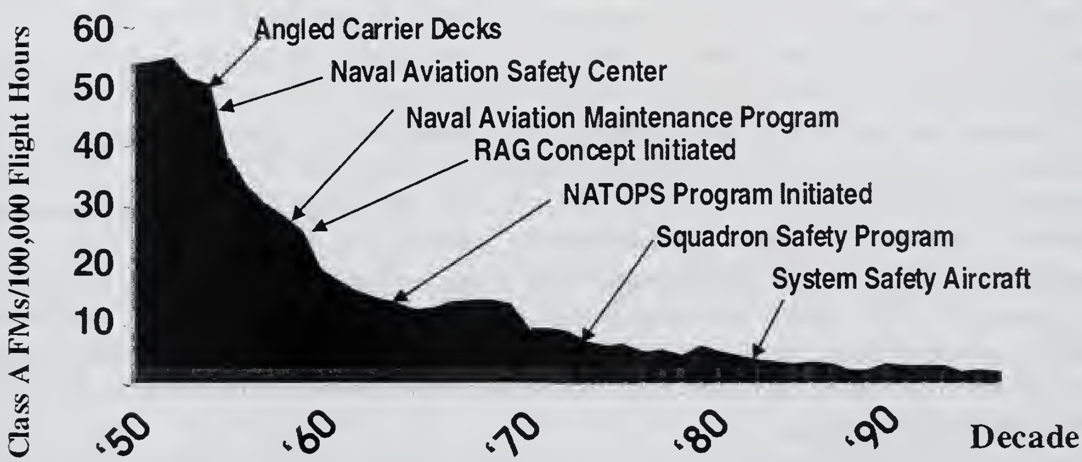

Figure 1. Naval Aviation Safety Initiatives (Naval Safety Center, 1999).

Nearly all aviation accidents involve some form of human error (Weigmann & Shappell, 1997), yet the predominance of accident reporting systems do not support the inclusion of data that pertains to any theoretical human error framework (Bruggink, 1996). While many experts believe human nature dictates that it is impossible to eliminate all human errors (Gertman & Blackman, 1994), there is more than enough latitude in the aviation industry for human errors to be reduced and benefits realized. Within the field of aviation there are three prevalent categories of human error present: supervisory, aircrew, and maintainer. A number of studies (Shappell & Wiegmann,

1997; Trollip & Jensen, 1991; Wickens, 1997) have offered theoretical models that have focused on aircrew-related error, leaving maintenance and its supervision as the much maligned "stepchild," often criticized, but seldom offered assistance in addressing its failings (Marx & Graeber, 1994). There have been various piecemeal attempts to address maintenance error; however, there has not been a coordinated approach grounded in the theoretical framework of accident causation (Marx, 1998). It is through such a theoretical framework that steps can be taken to avoid further occurrences of the same type of accident (Marx & Graeber, 1994). Should a framework be identified, a post hoc analysis of previous mishaps would be required first to determine the validity and reliability of the framework, and second, to enable the data to be analyzed from a maintenance perspective. In the event of the framework being successful in analyzing maintenance-related incident data, such a framework could be incorporated into existing mishap investigation procedures.

In response to the heightened awareness of human factors as a contributing element to a significant percentage of mishaps, Naval Aviation established a Human Factors Quality Management Board in 1996. The board's purpose was to analyze and improve the processes, programs and systems that impact human performance in Naval Aviation (Nutwell & Sherman, 1997). In addition to this, recent developments by the Naval Safety Center (NSC) in analyzing human errors contributing to Naval Aviation mishaps have resulted in the development of the Human Factors Analysis and Classification System (HFACS) taxonomy (Frazier, 1999). The HFACS taxonomy draws

upon concepts from various accident causation theories and aims to target areas for intervention by adequately representing factors that are precursors to accidents.

A "Maintenance Extension" of the original HFACS taxonomy, focusing on causation factors particular to the maintenance environment (Schmidt, Schmorrow & Hardee, 1997), was developed in order to classify factors that lead to maintenance-related mishaps (MRMs). The HFACS-ME model is based upon the original HFACS taxonomy as well as on current organizational and psychological theories of human error. HFACS-ME views a maintainer's performance as being influenced by a series of latent conditions (supervisory, maintainer, and working conditions) that can lead to an unsafe maintainer act, which in turn can lead to a mishap, ground damage, injury, or unsafe maintenance condition. Naval Aviation MRMs did not lend themselves to human factors analysis in their original form, and to overcome this situation, a post hoc analysis of contributing factors was conducted by two Naval Officers, well versed in the HFACS-ME taxonomy and experienced in maintenance operations. The two judges independently reviewed each MRM case, and a high level of agreement was achieved in coding of the MRMs. This result was an encouraging baseline that suggested not only that the mishaps were correctly coded, but that the HFACS-ME taxonomy appeared to be a sufficient tool for mishap data analysis.

Another significant work that incorporated the HFACS-ME taxonomy entailed the analysis of 470 Naval Aviation MRMs (Schmorrow, 1998). The analysis encompassed the mathematical modeling of the errors and used the models to (a) predict the frequency with which maintenance-based mishaps will occur in the future and (b) approximate the

potential cost savings from the reduction of each error type. It showed the utility of such an analysis in estimating potential return on investment of proposed intervention strategies (Schmidt, Schmorrow, & Figlock, 2000).

C. RESEARCH OBJECTIVE

The purpose of this study is to investigate human errors in Naval Aviation MRMs. There are two objectives: The first is to validate the model developed by Schmorrow (1998) that attempted to predict future mishaps as a stochastic model with a variable Poisson arrival process. The model predicted a mean number of MRMs for FY98 through to FY02. These predictions are compared to actual data collected since his study to determine its validity and a new predictive model is developed. Secondly, data analysis is conducted on the mishap data of the past ten years to determine if there are significant trends within the factors attributed to MRMs. Here, simple frequency counts giving the most prevalent types of MRM errors are replaced by a more complex analysis to identify the trends within these errors.

D. PROBLEM STATEMENT

Concerns posed by continued operating and training budget reductions and attempts to further decrease military aviation mishap rates have focused increasing interest on alternative areas for cost savings. This thesis conducts a human factors analysis to predict the occurrence of future MRMs and to analyze trends in causal factors. This study addresses the following questions:

1. Are the established stochastic models (Schmorrow, 1998) for predicting MRMs still valid in light of ensuing mishap data?

2. Are the established models (Schmorrow, 1998) the best models, or should the models be modified?

3. Can MRMs be adequately classified through a theoretical framework, permitting trends to be identified that reveal correlations between casual factors?

E. SCOPE AND LIMITATIONS

This study examines only those 599 Naval Aviation mishaps that were caused, partially or wholly, by maintenance errors. Additionally, only mishaps that occurred between FY90 and FY99 were included. The focus of this study is on maintenance-related errors committed by maintenance and line personnel that contribute to major mishaps; this may not depict the same pattern found in minor ones of less severity. Also, Limitations inherent in this study relate to the manner in which the data was massaged into a form conducive to conducting a human factors analysis. While there was a high level of agreement between judges in determining HFACS-ME codes relevant in reported mishaps, as the original data was not reported with the benefit of such a taxonomy, it is conceivable that not all of the contributing factors were reported.

F. DEFINITIONS

This study uses the following definitions, as described in the US Navy's OPNAV Instruction 3750.6Q (Department of the Navy, 1997):

Naval Aircraft. Refers to US Navy, US Naval Reserve, US Marine Corps, and US Marine Corps Reserve aircraft.

Mishap. A mishap is an unplanned event or series of events directly involving Naval Aircraft, which results in at least ten thousand dollars in cumulative damage to Naval Aircraft or any personnel injury.

Mishap Class. Mishap severity classes are based on personnel injury and property damage.

a. Class A. A mishap in which the total cost of property damage (including all aircraft damage) is $1,000,000 or greater; or a Naval Aircraft is destroyed or missing; or any fatality or permanent total disability occurs with direct involvement of Naval Aircraft.

b. Class B. A mishap in which the total cost of property damage (including all aircraft damage) is $200,000 or more, but less than $1,000,000; or which results in a permanent partial disability; or the hospitalization of five or more individuals.

c. Class C. A mishap in which the total cost of property damage (including all aircraft damage) is $10,000 or more but less then $200,000; or which results in an injury leading to one or more lost workdays.

Mishap Categories. Naval Aircraft mishap categories are defined as:

a. Flight Mishap (FM). Those mishaps in which there was $10,000 or greater DOD aircraft damage or loss of a DOD aircraft, and intent for flight for DOD aircraft existed at the time of the mishap. Other property damage, injury, or death may or may not have occurred.

b. Flight Related Mishap (FRM). Those mishaps in which there was less than $10,000 DOD aircraft damage, and intent for flight (for DOD aircraft)

existed at the time of the mishap, and $10,000 or more total damage or a defined injury or death occurred.

c. Aircraft Ground Mishap (AGM). Those mishaps in which no intent for flight existed at the time of the mishap and DOD aircraft loss; or $10,000 or more aircraft damage, or property damage, or a defined injury occurred.

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II. LITERATURE REVIEW

A. OVERVIEW

The initiatives and efforts behind the recent reductions in the number of Class A mishaps in Naval Aviation are to be applauded; however, there is scope for further improvement, especially in the area of human error. Analyzing and learning from human errors have the potential to raise levels of safety to new heights. When examining an accident involving human error there are many different theoretical approaches to choose from (Goetsch, 1996). Some are founded in industrial safety, while others are viewed from a complex systems perspective, emphasizing human factors and operator error. Alternatively, some approaches use models drawn from the domain of preventive medicine that employ epidemiological factors to analyze accidents, and yet again, other models utilize a combination of these approaches. Table 1 outlines some of the more robust approaches, which are discussed in detail.

Table 1. Theories of Accident Causation.

Source	Model	Approach	Focus
Industrial Safety	Heinrich – "Domino"	Linear	Task Analysis
Human Factors	Reason – "Swiss cheese"	Vertical	Human Error
Preventive Medicine	MacMahon – "Web of Causation"	Demographics	Situational Variables

B. ACCIDENT CAUSATION THEORIES

It was not until the 1930s, with the work of H. W. Heinrich, that a theoretical approach was applied to accident causation. In the original edition of his text *Industrial Accident Prevention* (Heinrich, 1931) he identified axioms of industrial safety that summed up his theory in ten postulates. His axioms gave rise to the first theoretical framework within which accidents could be viewed. While today these axioms may be viewed as being passé, they were revolutionary in his day. Almost all of today's theories on accident causation are based on Heinrich's work (Peterson, 1996). Accordingly, the less than earth-shattering impact his axioms have today pays tribute to the influence of his work and its proliferation through the safety culture of modern society.

Perhaps the most enduring concepts from Heinrich's work were his two fundamental beliefs: 1) the single largest reason behind accidents is people, and 2) the control of accidents is a management problem (Peterson, 1996). By virtue of his work, people began to view accidents as being the result of one or both of two things: an act and a condition. A paradigm shift followed that took the focus from physical preventative measures, such as machine guards, inspection and housekeeping, to a causation sequence that involved people and the situation or environment that surrounded them.

1. Heinrich's "Domino" Theory

Many consider the original accident causation theory to be Heinrich's "domino theory" (Goetsch, 1996). While contemporary research has outshone a number of the original concepts addressed in his axioms, many of today's widely accepted theories can trace their roots to Heinrich's work. With his domino theory, Heinrich viewed accidents

as occurring as a result of a related series of factors (or chain of events) that lead to the actual accident. Heinrich's original five-factor model (Heinrich, Petersen, & Roos, 1980), can be paraphrased as a five-step (or domino) sequence as follows (see Figure 2):

1. Lack of Control: This is a management issue where the emphasis is placed on the control exercised in a situation for an array of factors.
2. Basic Cause(s): This identifies the origin(s) of the causes and includes aspects such as human factors, environmental factors, or job-related factors.
3. Immediate Cause(s): This includes substandard practices and conditions that are symptoms of the basic causes.
4. Incident: This typically involves contact with the hazard, and for example, results in a fall or impact with moving objects.
5. Personal Injury and Property Damage: This includes lacerations, fractures, death, and material damage.

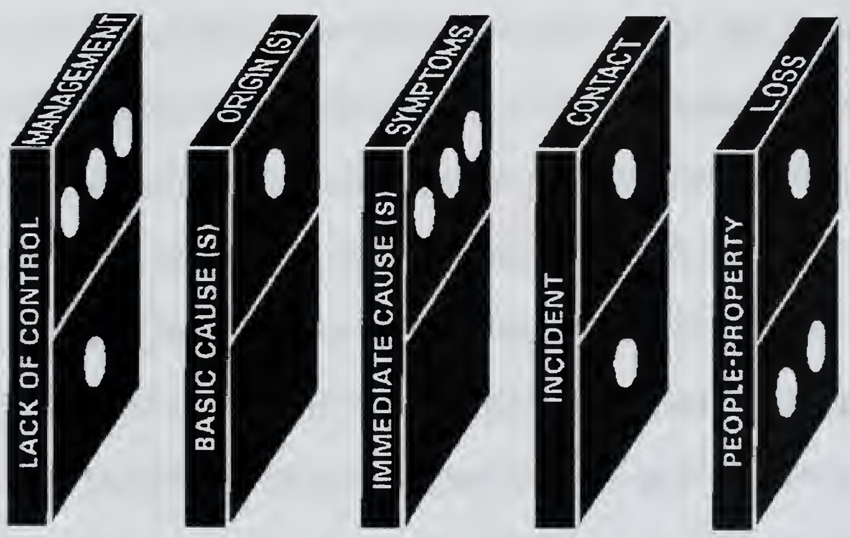

Figure 2. The Five-Step Domino Sequence (Bird, 1980).

Each step preempts the next, causing it to occur; much the same way as one domino falling causes the next domino in sequence to fall as well. Removal of the factors that comprise any of the first three "dominos" will effectively intervene to prevent the accident. This theory is built upon two central precepts: 1) injuries are caused by the action of preceding factors; and 2) removal of the central factor (unsafe act/hazardous condition) negates the action of the preceding factors, and in doing so, prevents accidents and injuries (Goetsch, 1996).

2. Reason's "Swiss Cheese" Model

Another widely accepted perspective on accident causation was developed by Reason (1990). Here a human factors approach was employed to view the vertical association of a collection of factors that eventually lead to an accident. His "Swiss cheese" model distinguishes between two types of errors: 1) active failures, whose effects are felt immediately, and 2) latent conditions, whose effects may lie dormant until triggered later, usually by other mitigating factors. The presence of defenses or safeguards in a system can usually prevent the effects of latent conditions from being felt by closing the "window of opportunity" during which an active failure may be committed. Latent conditions "set the stage" for the accident while active failures tend to be the catalyst for the accident to finally occur. The model can be thought of as slices of Swiss cheese lined up, with each vertical slice representing a defense layer (e.g. training, good management, teamwork, etc.) and each hole representing an active failure or latent condition in that defense (see Figure 3). Should a situation where holes line up come to pass, an accident will occur.

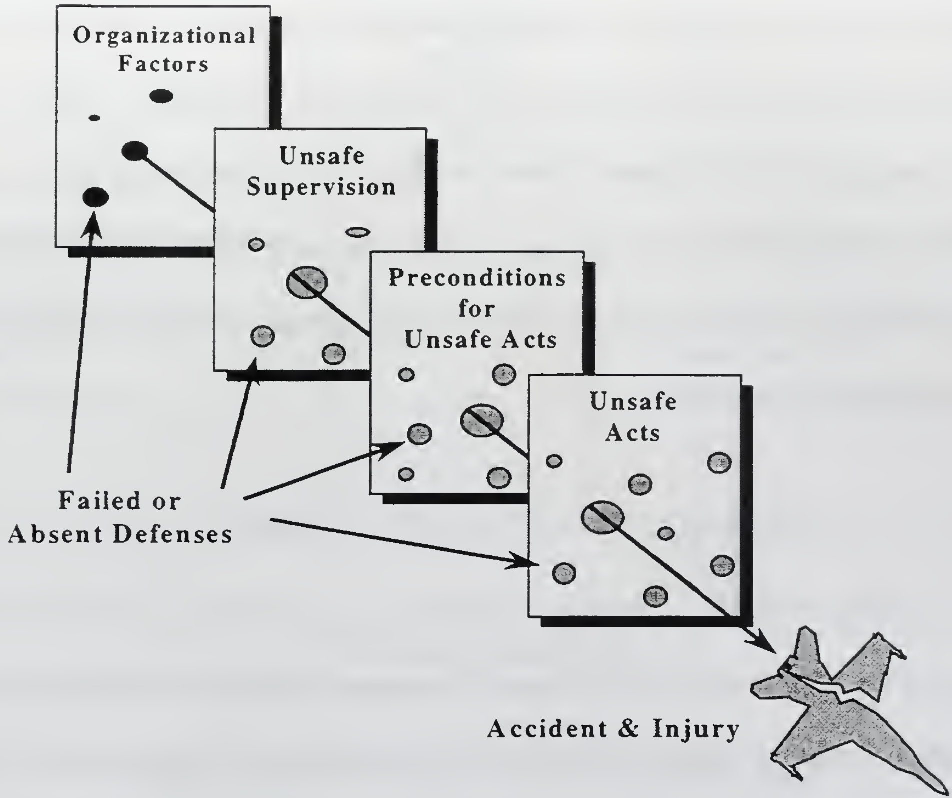

Figure 3. Reason's "Swiss Cheese" Model (Naval Safety Center, 1996).

Reason (1997a) determined that his model was not static, but rather a metaphor that is best represented by a moving picture, with each defensive layer coming in and out of contention according to the characteristics of the situation. The underlying system that causes an event to occur is characterized by Reason (1997a) as having three levels: the person (unsafe acts), the workplace (error-provoking conditions), and the organization (error-establishing conditions). Organizational factors are seen as the starting point for an accident. Here strategic decisions, and their associated processes such as resource allocation, budgeting, forecasting and planning, are initiated. These processes are then shaped and influenced by the corporate culture before being communicated throughout the organization to the individual workplaces. At the workplace, corporate processes

manifest themselves as insufficient staffing, undue time pressures, inadequate equipment, insufficient training and unworkable and ambiguous procedures. These workplace factors combine with the natural human tendency to commit errors and violations to produce the unsafe acts. Many unsafe acts are committed, either intentionally or unintentionally; however, very few of them actually create holes in the defenses that lead to accidents (Reason, 1997a).

3. MacMahon's "Web of Causation" Paradigm

Through adopting a broader perspective on the cause of accidents, available theories of accident causation have been augmented to include an epidemiological theory of accident causation (Goetsch, 1996). These models focus upon the many interactions between the host, or in this case the individual, and his/her environment. Models based on this theory are used to establish causal relationships between personal characteristics, environmental factors, and accidents (Mausner & Bahn, 1974). The key components of the epidemiological theory of accident causation are: 1) predisposition characteristics; and 2) situational characteristics (Goetsch, 1996). When these characteristics are combined, they can either prevent or result in conditions that can cause an accident (see Figure 4). An example cited by Goetsch sees an employee who is particularly susceptible to peer pressure (predisposition characteristic) is pushed by his co-workers (situational characteristic) to speed up his operation, the result of which would be the increased probability of an accident.

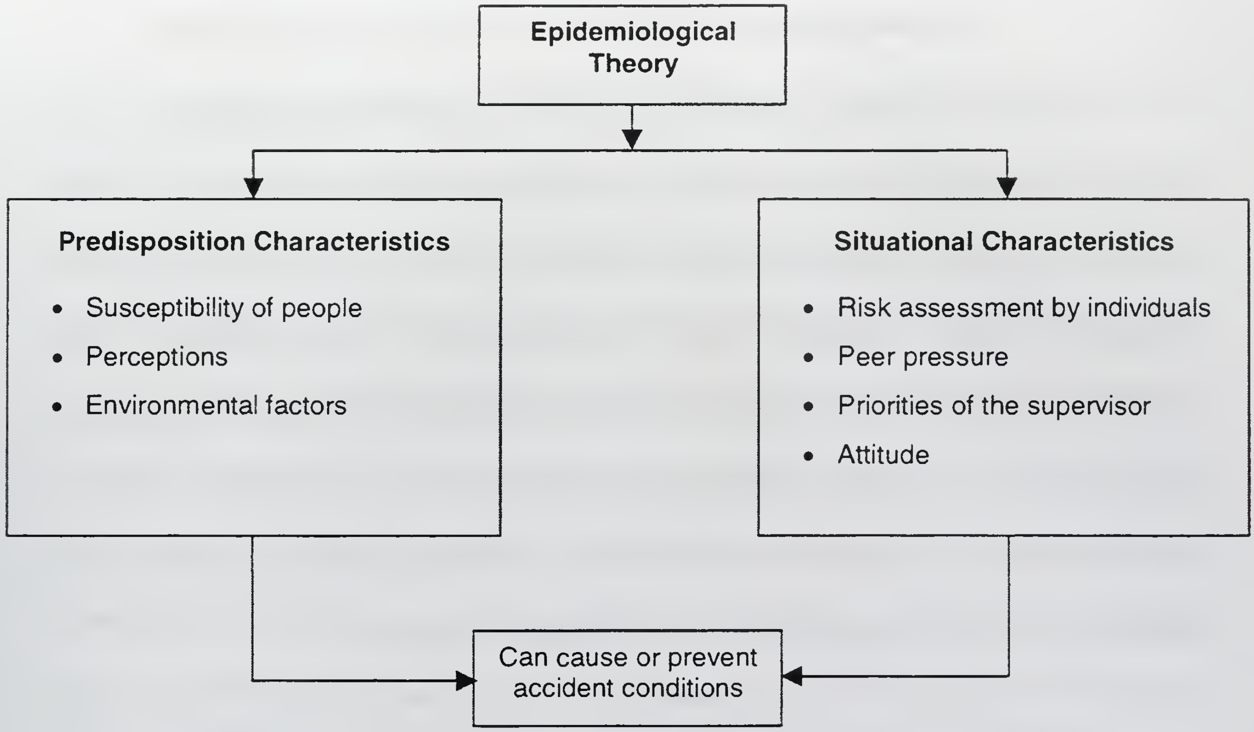

Figure 4. Epidemiological Theory (Goetsch, 1996).

MacMahon used the notion of a "web of causation" to postulate that accidents never depend on single isolated causes, but rather develop as the result of chains of causation in which each link itself is the result of a complex "genealogy of antecedents" (Mausner & Bahn, 1974). A significant number of these antecedents combine to conceptually form a complex web of causation factors. The breaking of interconnections within the web at various points would serve to interrupt the flow which would lead to an accident. The multitude of factors connecting the web in MacMahon's model support the notion that no one factor can be solely labeled as the cause of the accident.

4. Combined Approach

As accident causation is still tied to the world of theories rather than fact, it would be overly demanding to require that any one model explain all accidents (Goetsch, 1996). A given model may adequately describe a number of accidents; however, it would not be expected to describe all accidents, as an accident typically combines aspects of several models. Accordingly, it is considered that only a composite model that could represent a greater variety of causation factors would accurately model all accidents. Just as an accident is usually described by an accumulation of factors, modeling an accident could quite understandably be described by an accumulation of theories.

Accepting the premise that there is a preferred combined approach to accident causation is only an intermediate step in understanding the causes of accidents (Goetsch, 1996). The next step is to classify these causes within a taxonomy that is flexible and robust enough to adequately account for the underlying causation data. Data classified by such a taxonomy would also be required to stand up to the rigors of statistical analysis in order to determine not only the most frequent casual factors, but also trends relating to accidents that could identify areas to target intervention strategies (Marx & Graeber, 1994). The fundamental goal in understanding accident theory is to be able to develop a sound theoretical framework for reporting accidents in the hope of analyzing the causation factors and preventing similar occurrences in the future.

C. MAINTENANCE RELATED MISHAPS

In recent years many researchers have attempted to focus the theories of accident causation on understanding maintenance-related mishaps (MRMs) in the aviation industry (Marx, 1998). The aim of these efforts was to change the way these accidents were investigated. Previously, there had been a commonly held notion that every error could be traced back to a basic set of actions and associated conditions that precipitated the error (Goetsch, 1996). It was realized that this was a simplistic view of the world as most errors have multiple causes. Additionally, it was realized that traditional investigation techniques, while appropriate for identifying the causes of equipment failures, did not have the same success with human error-related accidents (O'Connor & Bacchi, 1997). Typically, traditional investigations would effectively end when the cause pointed to human error, with no effort expended in attempting to explain why the error occurred.

Marx (1998), in a review of investigation and analysis systems for aircraft maintenance error, highlighted the need for human factors investigation and reporting in order for the industry to understand why people make certain mistakes. The review also laments that although human factors investigation methods are acknowledged as being superior, they have not been widely adopted, especially in the US. Marx (1998) cites the following reasons for the alleged unpopularity: tendency to place blame, inability to see through proximate causes to underlying causes, and an over-emphasis on static factors such as who, what and when.

Many experts agree (Gertman & Blackman, 1994; Redmill & Rajan, 1997; Helmreich & Merritt, 1998;) that Reason's model is useful in explaining accidents; however, it does not provide a means of delineating precursors to accidents (Weigmann & Shappell, 1997). While it is regarded that these types of analysis systems are heading in the right direction, more is expected. There is a requirement for a theoretical framework that allows for the explanation of accident causation in such a manner as to permit the identification of key reasons (and for the explanation of those reasons). It is through such an approach that steps can be taken to avoid further occurrences of the same type of accident.

D. HFACS MAINTENANCE EXTENSION

Efforts at the Naval Safety Center in analyzing human errors contributing to Naval Aviation mishaps have resulted in the development of the Human Factors Analysis and Classification System (HFACS) taxonomy (Weigmann & Shappell, 1997). The aim of this taxonomy is to identify areas for potential intervention by fully describing factors that are precursors to accidents. The HFACS taxonomy draws upon concepts from Heinrich's "Domino" theory (Heinrich 1931; Heinrich, Petersen, & Roos, 1980) and Reason's "Swiss Cheese" model (Reason, 1990; 1997b) and synthesizes them into one succinct model, which also arguably encompasses the essence of MacMahon's "Web of Causation" model (Mausner & Bahn, 1974). The HFACS model provides for recognizing a set of conditions within which system operators perform. The model also accounts for interrelationships among conditions as well as an overall sense of order or implied hierarchy.

This taxonomy was subsequently adopted, adapted, and augmented to classify factors that lead to maintenance-related mishaps (Schmidt, 1996). The "Maintenance Extension" of the original HFACS taxonomy focuses on causation factors particular to the maintenance environment. These aspects and their relevant sub-section classifications are given in Table 2. In a manner similar to Reason's model, the HFACS-ME model views a maintainer's performance as being influenced by a series of latent conditions (supervisory, maintainer and working conditions) that can lead to an Unsafe Maintainer Act. This Act can in turn lead to a mishap, injury or an unsafe maintenance condition as depicted in Figure 5. The HFACS-ME taxonomy not only encompasses the notion of multiple causation and a chain of events/influence, but also the hardware and working conditions involved – as is the case with the "SHEL" model (Edwards, 1981; Hawkins, 1997).

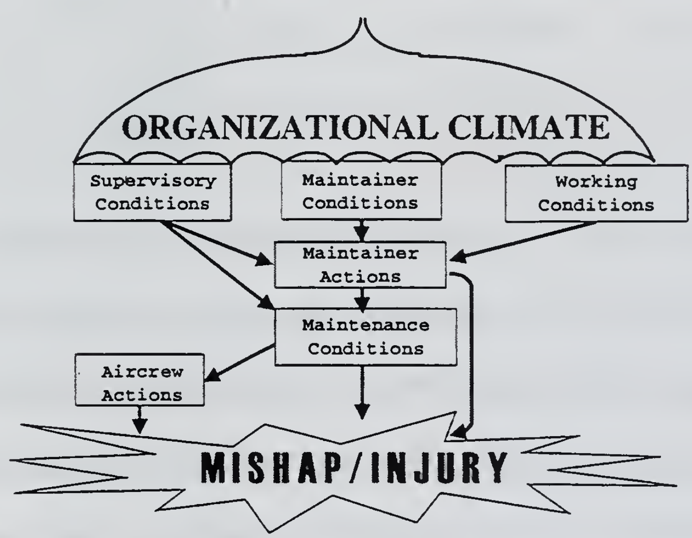

Figure 5. HFACS Maintenance Extension Model (Schmidt, 1996).

Table 2. Original HFACS-ME Taxonomy (Schmidt, 1996).

First Order	Second Order	Third Order
Supervisory Conditions	Unforseen	Hazardous Operations Inadequate Documentation Inadequate Design
	Squadron	Inadequate Supervision Inappropriate Operations Failed to Correct Problem Supervisory Violation
Maintainer Conditions	Medical	Mental State Physical State Physical/Mental Limitation
	Crew Coordination	Communication Assertiveness Adaptability/Flexibility
	Readiness	Preparation /Training Qualification/Certification Violation
Working Conditions	Environment	Lighting/Light Weather/Exposure Environmental Hazards
	Equipment	Damaged Unavailable Dated/Uncertified
	Workspace	Confining Obstructed Inaccessible
Maintainer Acts	Error	Attention Memory Knowledge/Rule Skill
	Violation	Routine Infraction Exceptional

HFACS-ME consists of four broad human error categories, three latent: Supervisory Conditions (e.g. inadequate supervision), Maintainer Conditions (e.g. preparation/training), Working Conditions (e.g. lighting/light); the fourth Maintainer Acts (e.g. skill error), is active. The three orders of maintenance error (first, second, and third) reflect a decomposition of the error types from a macro to a micro perspective. Each successive order provides for greater granularity, serving the respective purposes of identifying problem areas, prioritizing potential targets, and tailoring intervention

strategies. A brief description of the original taxonomy with illustrative examples is included in Appendix A.

The HFACS-ME taxonomy was initially applied to Naval Aviation Class A FMs for FYs 90-97 (Schmidt, Schmorrow, & Hardee, 1997). This study revealed that HFAC-ME was effective in capturing the nature of, and relationships among, latent conditions and active failures present in Class A MRMs. It was found that 75 percent of all Naval Aviation Class A mishaps reported an instance of Maintainer Error, whereas 40 percent reported Maintainer Violations. Squadron Supervisory conditions were reported in 67 percent of these mishaps, with Organizational Supervisory conditions reported in 21 percent. In viewing the results, it was felt that the existing investigation and reporting process/system are not conducive to determining the impact of Maintainer and Working conditions.

Schmorrow (1998), in a study of 470 Naval Aviation MRMs, showed five second-order HFACS-ME causal dimensions — Organizational Supervision, Squadron Supervision, Maintainer Crew Coordination, Maintainer Error, and Maintainer Violation — are present in over 95 percent of Class A, B, and C MRMs. He employed stochastic modeling to forecast the frequency of MRMs given preservation of the status quo and the projected frequency given reductions of 10, 20 and 30 percent of certain taxonomy categories. He estimated that a reduction of 10 percent in any single error category would result in an average cost savings of over one million dollars annually. Overall, this study demonstrated the potential for calculating the return on investment for specified MRM control measures (Schmidt, Schmorrow, & Figlock, 2000).

Teeters (1999) also employed the HFACS-ME taxonomy, in this instance to identify causal factors in 124 maintenance-related incidents (including MRMs, reported hazards, and personal injuries) of the Naval Reserve Fleet Logistic Support Wing. The aim of this study was to determine if HFACS-ME would be successful in capturing causal dimensions in MRMs of all severity levels. With the assistance of the taxonomy he identified two primary problem areas: 1) contractor oversight and 2) procedural violations. Subsequently, this enabled the projection of future MRM occurrences and the potential impact of targeted interventions (Schmidt, Figlock, & Teeters, 1999).

E. SUMMARY

The key concept in thinking about human error reduction is that human beings do not commit errors because they are unintelligent or because they are wrong (Peterson, 1996). In many instances, errors are committed when in fact they were perceived to be the logical thing to do as the situation presented itself. In essence, human errors are caused by the situations in which people find themselves – physical situations, psychological situations, environmental situations, and so on. Once errors are perceived in such a manner, the next step is to be able to adequately comprehend why accidents occur and how human error plays a part.

While there are many theories of accident causation, there is a central theme that is common to the majority of them: accidents are the product of multiple contributing factors, not one primary factor. Additionally, rather than relying on one particular model that emphasizes a certain facet of accident causation, a combined approach appears to provide a more robust perspective. This is particularly the case with understanding Naval

Aviation MRMs. In this instance, the HFACS-ME taxonomy has been successfully utilized to analyze MRMs and categorize their causal dimensions. Once common error forms are identified in MRMs, it has also been demonstrated that the results can be successfully used to model and forecast future occurrences and the possible benefits of implementing planned intervention measures.

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III. METHODOLOGY

A. RESEARCH APPROACH

This study involves the analysis of an existing database of Naval Aviation mishap reports maintained by the Naval Safety Center (NSC). The reports contain data relating to the mishap as compiled by accident investigators. As the data contained in the reports does not lend itself to human factors analysis in its original form, a post hoc analysis of contributing factors is conducted. Each maintenance-related mishap (MRM) is evaluated and the respective Human Factors Analysis and Classification System Maintenance Extension (HFACS-ME) codes corresponding to the causal factors identified in the investigation are tabulated for analysis. Similar to the previous research by Schmorrow (1998), stochastic models of MRMs are constructed and evaluated to predict the occurrence of future MRMs. Additionally, a trend analysis of MRM casual factors is undertaken. From these two analyses, the number of MRMs over the next five fiscal years is estimated, and trends within MRMs identified.

B. DATA COLLECTION

1. Naval Aviation Safety Program

The Department of the Navy's (1997) Naval Aviation Safety Program (*OPNAV Instruction 3750.6Q*) details the Naval Aviation Safety Program and its manner of implementation. It establishes safety program requirements, including those specifying mishap and hazard investigation, reporting, and analysis. Mishap investigation reports are produced for all Class A, B and C mishaps in an attempt to identify the contributing

factors and to recommend intervention strategies as appropriate. It is from these reports that data for this study was obtained, with the aim of gaining an overall perspective of mishap contributing factors, rather than a case by case analysis.

2. Safety Information Management System Database

The NSC maintains a database comprised of codified incident reports that are accessed via the Safety Information Management System (SIMS). Database information is entered manually by NSC staff from original incident reports. SIMS has the capacity to produce a variety of on-line and batch-processed reports, including frequency counts on specified data fields, flight hour data, and narrative event summaries.

3. Data Purification

Class A, B, and C MRM data for FY90 to FY99 was obtained from the SIMS database, augmented to incorporate HFACS-ME codes pertaining to each of the MRM casual factors, and manually entered into a computer database. The HFACS-ME codes were further augmented at the third-order level to better accommodate factors observed in the more minor class B and C MRMs that are mainly FRMs and AGMs respectively (see Appendix B). This did not affect the second-order categories used for the trend analysis in this study. From the computer database, the data was imported into data analysis software for subsequent stochastic modeling and categorical data analysis. Additionally, the data in the database was used to prototype the Maintenance Error Data Analysis and Reporting Tool (MEDART), which was developed by the author in conjunction with this study. The purpose of the MEDART is to provide a readily accessible reporting and

analysis tool for aviation maintenance-related safety personnel. Using the tool, they can generate a myriad of summary reports in order to gain insight into potential problem areas from which they could consider implementing local mishap intervention strategies (see Appendix C for a discussion of the prototype software tool).

C. DATA ANALYSIS

The first part of the study investigates the frequency of MRMs and associated HFACS-ME codes, attempting to validate Schmorrow's (1998) models. Whether existing stochastic models with a variable Poisson arrival process prove to be sufficient for predicting the occurrence of future mishaps, or they require modification, the resultant output is a predicted mean number of MRMs for FY00 through to FY04. Secondly, data analysis is conducted on the MRM data of the past ten years to determine if there are significant trends within the casual factors attributed to MRMs. Simple frequency counts giving the most prevalent types of MRM errors are replaced by a more complex analysis to identify the trends within these errors. For instance, anecdotal evidence suggests that there is a possible correlation between the occurrence of an unintentional error relating to a maintainer's lack of training and the absence of adequate supervision for that maintainer. Here, stochastic models, exploratory data analysis, and conditioning are utilized to summarize the MRMs and evaluate trends in the casual factors.

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IV. RESULTS

A. OVERVIEW

As previously stated, this study is divided into two main areas of investigation: model validation and trend analysis. Schmorrow (1998) focused on investigating the frequency with which maintenance-related mishaps (MRMs) occur in an attempt to devise an appropriate model to describe the underlying arrival process associated with those accidents. He considered models such as the Poisson process with homogenous and non-homogenous piece-wise constant rates, a moving average estimator, and a variable Poisson process. Each of these models was tested for fit using a modified denominator-free chi-squared (χ^2) statistical test which is considered a superior test to the classical χ^2 test when the data values are small and include zeros (Freeman & Tukey, 1950). After evaluating the models, he found the variable Poisson process model to provide the best fit in describing MRMs

The second area of focus, trend analysis, involved the exploration of the human factor causal dimensions attributed to the MRM data. In this instance, an analysis was conducted on the pairwise dependencies of second-order Human Factors Analysis and Classification System Maintenance Extension (HFACS-ME) categories. Second-order categories were chosen for the analysis in preference to first-order, which were considered to give insufficient granularity, and third-order, which were considered to be too sparsely distributed. This analysis revealed relationships between the causal factors attributed of MRMs. Correlation matrices, intersection matrices and conditional relationships were investigated to determine the these relationships.

During the course of this study it was identified that certain HFACS-ME classifications should be renamed to more closely reflect the scope of the grouping, while additional third-order HFACS-ME categories are required in order to give a more precise representation of the errors present in MRMs. Subsequently, several categories were added to the taxonomy and others renamed. An updated table of HFACS-ME classifications is given in Appendix B.

B. VALIDATING PREVIOUS STOCHASTIC MODELS

The variable Poisson process model employed by Schmorrow (1998) generates an estimator based on a function fitted to historical data (Devore, 1995). Upon fitting a curve to historical data, the hypothetical Poisson process mean is predicted. This value at some month t is assumed to come from a Poisson process with mean λ which follows the exponential decay equation $\log(\lambda_t) = \beta_0 + \beta_1 * t$. Schmorrow (1998) used a maximum likelihood function to estimate values for β_0 and β_1, however, this study employs a generalized linear model that produces similar results. Variable Poisson process models are derived for mishap type as well as mishap class, and the coefficients of the equations pertaining to each of these models are given in Table 3 (*note*: the coefficients are presented in the form $\log(\lambda_t) = \beta_0 + \beta_1 * t$, rather than in the original $\lambda_t = \beta_0 * \exp(\beta_1 * t)$ format). In each instance, the previous study found that the modified denominator-free χ^2 goodness of fit test produced results that were above the 0.05 threshold established for the suitability of the models.

Table 3. Coefficients of the Previously Fitted Variable Poisson Process Models for MRMs (Schmorrow, 1998).

Mishap Classification	β_0	β_1
Flight	0.83	-0.85
Flight-Related	-0.35	-1.40
Aircraft-Ground	1.46	-0.91
Class A	0.02	-1.08
Class B	-0.36	-0.46
Class C	1.93	-1.38
Total	1.97	-0.93

It is observed that given the same period (i.e., FY90 – FY 97), the number of MRMs in each class and type reported in the previous study differed from that obtained in this study. This is an understandable occurrence in some situations as, on occasion, mishaps are re-evaluated by the relevant authorities and re-classified. It was determined that in the majority of instances, some materiel-related mishaps were previously included in the data. The corrected distributions of MRMs by class and type for the period FY90 – FY99 are given in Table 4. Mishap class and type data is also displayed graphically in Figure 6, where it can be seen that 77 percent of all MRMs are Class C mishaps; alternatively, it is shown that 52 percent of all MRMs are Aircraft-Ground mishaps.

Table 4. MRMs by Class and Type for FY90-FY99.

	Flight	Flight-Related	Aircraft-Ground	Total
Class A	61	1	12	74
Class B	24	11	31	66
Class C	147	39	273	459
Total	232	51	316	599

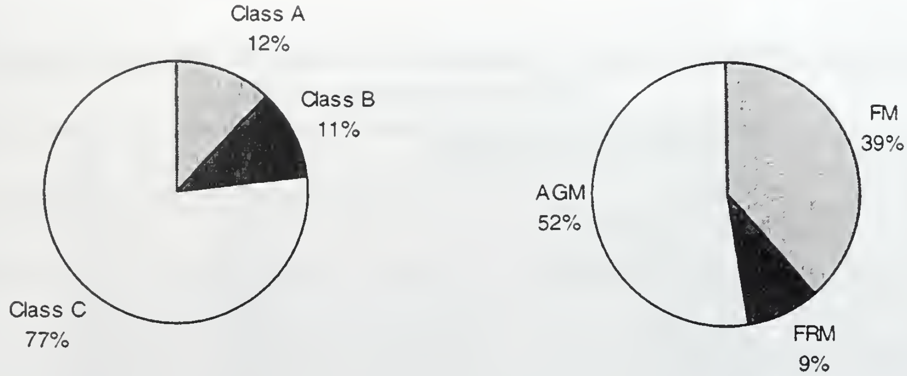

Figure 6. MRMs by Class and Type for FY90- FY99.

In addition to the slightly inflated number of MRMs, it was discovered that previously, only MRMs attributed to tactical aircraft (e.g., F/A-18) and rotary wing aircraft (e.g., H-60) were included. It is understandable that with the inclusion of all Naval Aviation aircraft, the predicted numbers of MRMs for the period FY98 – FY99 in the original model were not as close to the actual counts observed. As the models are derived from the Poisson distribution, predicted values within $2\sqrt{\hat{\lambda}}$ of actual values are regared as being acceptable. Table 5 shows that the differences between the figures for Class B MRMs are negligible; however, most of the other categories differ significantly. Accordingly, it can be considered that the previously developed variable Poisson process models did not adequately predicted the occurrences of MRMs for this two-year period.

Table 5. Predicted Versus Actual MRMs for FY98 – FY99.

Mishap Classification	FY98 Predicted	FY98 Actual	FY99 Predicted	FY99 Actual
Flight	11.6	26	10.4	17
Flight-Related	1.8	3	1.5	4
Aircraft-Ground	20.2	24	18.1	20
Class A	4.1	7	3.6	5
Class B	5.3	5	5.0	4
Class C	20.0	41	17.0	32
Total	33.5	53	30.0	41

As the previous models were not as precise as anticipated, more accurate models were, this time based on the current database. Mishap data from the 120 months of the period FY90 – FY99 was input into a Poisson generalized linear model, which utilized a logarithmic link function. Table 6 shows the values of the coefficients that were calculated, the probabilities obtained, and the suitability of the models. The denominator-free χ^2 goodness of fit test (see Appendix E for the S-Plus function that was used to calculate the probability of fit) was employed to determine the suitability of the models, with the 0.05 set as the level of significance.

Table 6. Validation of Variable Poisson Process Model for FY90 – FY99.

Mishap Classification	β_0	β_1	$P\{\chi^2_{118} \geq \hat{\lambda}_t\}$	Suitability
Flight	1.014	-0.006	0.155	Not unusual
Flight-Related	-0.151	-0.013	0.999	Not unusual
Aircraft-Ground	1.410	-0.008	0.251	Not unusual
Class A	0.081	-0.010	0.967	Not unusual
Class B	-0.245	-0.006	0.997	Not unusual
Class C	1.762	-0.008	0.062	Not unusual
Total	2.039	-0.008	0.008	Unusual

While most models that were developed were regarded as being adequately fitting the data, the model corresponding to total mishaps was not evaluated as being suitable. This revelation is mildly alarming; however, a closer examination of the other (subordinate) models reveals that they are declining at different rates. Accordingly, it is understandable that this aggregated model could not be fit as closely to the data. In review, it is considered that Schmorrow's (1998) models and his subsequent predictions were not accurate. The models that were developed in this study have an advantage over the previous models in that they were developed with the benefit of an additional two

years of data. Additionally, they were produced from a database that is more complete and accurate. Figure 7 shows the equation fitted to the total MRM data, while graphs for mishap class and type are found in Appendix F.

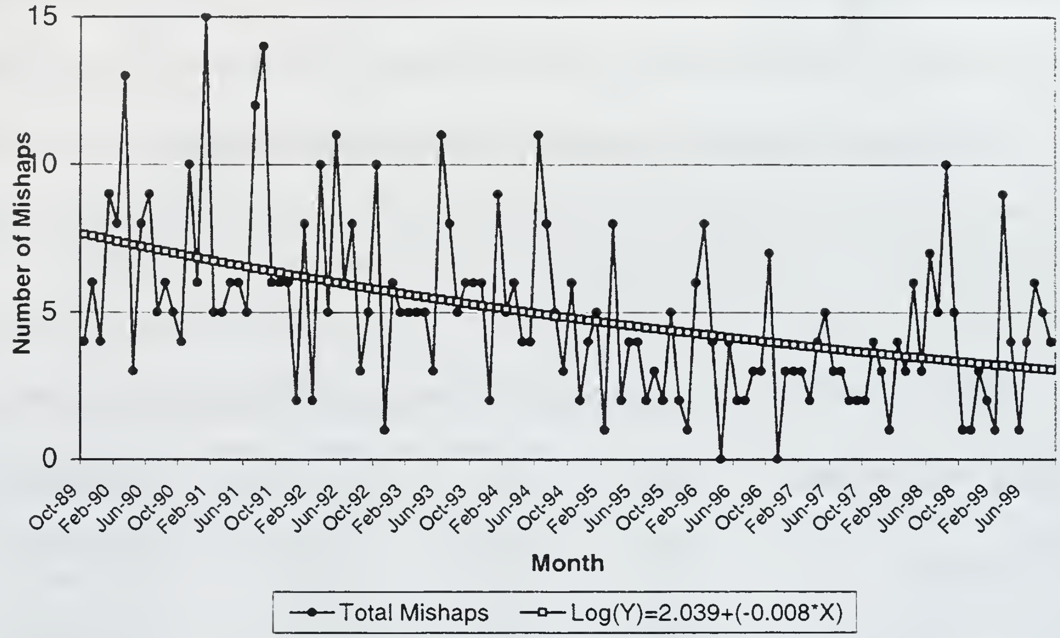

Figure 7. Variable Poisson Process Model for Total MRMs

C. MISHAP OCCURRENCE PROBABILITIES AND PREDICTIONS

The values obtained in evaluating the equations derived by the variable Poisson process model represent the means of the hypothetical Poisson process that in turn describes the way in which the MRMs occur. These means can be used to predict the probability of the occurrence of a particular class, or type, of future MRM. Accordingly, probability tables can constructed and be utilized to predict the likelihood of these MRMs and provide an insight into a conceivable environment facing Naval Aviation in the near future. Table 7 presents a summary of the probability tables found in Appendix G.

Table 7. Predicted Average Monthly MRM Probabilities for FY00.

Mishap Classification	Number of Maintenance-Related Mishaps 0	1	2	3	4	5	6
Flight	0.29	0.36	0.22	0.09	0.03	0.01	0.00
Flight-Related	0.85	0.14	0.01	0.00	0.00	0.00	0.00
Aircraft-Ground	0.22	0.33	0.25	0.13	0.05	0.01	0.00
Class A	0.75	0.22	0.03	0.00	0.00	0.00	0.00
Class B	0.70	0.25	0.04	0.01	0.00	0.00	0.00
Class C	0.11	0.24	0.27	0.20	0.11	0.05	0.02

By expanding the timeframe of the predictions given in Table 7 to one that encompasses the next five years, a more pertinent overview of the potential impact of MRMs can be gleaned. The hypothetical expected number of MRMs per year were calculated for the period FY00 – FY04 using the aforementioned Poisson process model. Summing the hypothetical monthly means generated by the model gives the expected number of MRMs per FY (see Table 8). To avoid the dilemma of using a reportedly unsuitable model, the model pertaining to total MRMs was not used to obtain the totals in Table 8. As total MRMs is equal to the sum of either FMs, FRMs and AGMs or Class As, Bs, and Cs, the total predicted MRMs are derived from individually summing the predicted MRMs for mishap class and mishap type and then averaging these two figures.

Table 8. Predicted MRMs for FY00 – FY04.

Mishap Classification	00	01	02	03	04
Flight	15.0	13.9	12.9	12.0	11.1
Flight-Related	1.9	1.6	1.4	1.2	1.0
Aircraft-Ground	18.1	16.4	14.9	13.6	12.4
Class A	3.5	3.1	2.7	2.4	2.1
Class B	4.3	4.0	3.7	3.4	3.2
Class C	27.1	24.7	22.6	20.6	18.9
Total	35.0	31.9	29.1	26.6	24.4

D. DATA EXPLORATION AND TREND ANALYSIS

The next phase of this study involved an attempt to determine relationships between the occurrences of the ten second-order HFACS-ME categories. Each MRM was evaluated to assess which of the ten second-order categories were considered to be mishap causal factors (see Table 9 for a summary of second-order HFACS-ME categories by mishap classification). Each evaluation was recorded as a binary row vector, thus indicating the presence or absence of each particular second-order category. This resulted in a 599 by 10 binary matrix, with MRMs during the period FY90 – FY99 defining the rows and second-order HFACS-ME categories defining the columns.

Initially, the relationships between the categories were viewed by taking the binary asymmetric matrix and using it to create a correlation matrix (see Table 10). Scanning this matrix revealed that the highest correlation occurred between Squadron Supervisory Conditions (SQN) and Maintainer Violation (VIO), with a correlation of 0.320. Other notable correlates were Environmental Working Conditions (ENV) and Workspace Working Conditions (WRK) at 0.284 and Squadron Supervisory Conditions (SQN) and Maintainer Error (ERR) at 0.211.

Table 9. Second-Order HFACS-ME Categories by Mishap Classification FY90 - FY99

Mishap Classification	Organizational	Squadron	Medical	Crew Coordination	Readiness	Environment	Equipment	Workspace	Error	Violation
Flight	127	106	5	14	6	0	3	1	128	69
Flight-Related	22	17	0	3	0	0	0	0	27	12
Aircraft-Ground	82	211	38	52	9	8	13	1	154	161
Class A	39	50	4	7	3	0	0	0	36	30
Class B	33	44	8	3	1	0	0	0	39	23
Class C	159	240	31	59	11	8	16	2	234	189
Total	462	668	86	138	30	16	32	4	618	484

Table 10. Correlation Matrix for the Reporting of Second-Order HFACS-ME Categories in FY90 – FY99.

	ORG	SQN	MED	CRW	RDY	ENV	EQP	WRK	ERR	VIO
ORG	1.000	0.084	-0.070	-0.012	0.035	-0.032	0.097	-0.042	0.104	0.032
SQN		1.000	0.029	0.175	0.084	-0.011	0.066	-0.051	**0.211**	**0.320**
MED			1.000	0.156	-0.029	0.058	0.031	-0.015	-0.059	0.024
CRW				1.000	-0.038	-0.035	0.056	-0.020	0.176	0.167
RDY					1.000	0.143	0.104	-0.008	0.090	0.003
ENV						1.000	-0.016	**0.284**	-0.045	-0.027
EQP							1.000	-0.009	0.043	0.041
WRK								1.000	-0.049	-0.040
ERR									1.000	0.008
VIO										1.000

Next, the binary asymmetric matrix was multiplied by its transpose to compute an upper diagonal matrix (see Table 11). This resultant matrix defines the number of MRMs that cite the combination given by the second-order category indicated by the row, with the second-order category given by the column. For example, 62 MRMs cited both Organizational Supervisory Conditions (ORG) and Maintainer Error (ERR) as causal

factors. Figures on the main diagonal represent the number of MRMs that cite the corresponding HFACS-ME category.

Table 11. Number of MRMs Citing the Second-Order Category of the Ith Row With the Second-Order Category of the Jth Column.

	ORG	SQN	MED	CRW	RDY	ENV	EQP	WRK	ERR	VIO
ORG	142	63	4	12	3	1	6	0	62	42
SQN		182	11	28	5	2	6	0	89	83
MED			25	7	0	1	1	0	6	8
CRW				43	0	0	2	0	27	22
RDY					7	1	1	0	5	2
ENV						6	0	1	1	1
EQP							10	0	5	4
WRK								2	0	0
ERR									172	48
VIO										131

Each element of the upper diagonal matrix given in Table 11 was then divided by the total number of MRMs to reveal a proportional matrix (see Table 12). This matrix gives the proportion of MRMs that cite the combination given by the second-order category indicated by the row, with the second-order category given by the column. The more significant combinations of categories are seen more readily using this method, with Squadron Supervisory Conditions (SQN) and Maintainer Error (ERR) reported in 14.9 percent of mishaps being the most frequently occurring pairing of categories. Squadron Supervisory Conditions (SQN) and Maintainer Violation (VIO) combinations were also quite prevalent at 13.9 percent.

Table 12. Proportional Matrix of Pairwise Combinations of Second-Order HFACS-ME Categories for FY90 – FY99 MRMs.

	ORG	SQN	MED	CRW	RDY	ENV	EQP	WRK	ERR	VIO
ORG	0.237	0.105	0.007	0.020	0.005	0.002	0.010	0.000	0.104	0.070
SQN		0.304	0.018	0.047	0.008	0.003	0.010	0.000	**0.149**	**0.139**
MED			0.042	0.012	0.000	0.002	0.002	0.000	0.010	0.013
CRW				0.072	0.000	0.000	0.003	0.000	0.045	0.037
RDY					0.012	0.002	0.002	0.000	0.008	0.003
ENV						0.010	0.000	0.002	0.002	0.002
EQP							0.017	0.000	0.008	0.007
WRK								0.003	0.000	0.000
ERR									0.287	0.080
VIO										0.219

Another important component of the analysis of trends within the data is in observing conditional proportions of causal factors that occur in mishaps (see Table 13). In this instance, the value obtained from the table represents the proportion of MRMs citing the causal factor identified by the row, given that mishap cite the causal factor, as identified by the column. By way of an example, should an MRMs cite Environmental Working Conditions (identified by the column ENV) as a causal factor, it is predicted that 33.3 percent of occurrences will also cite Squadron Supervisory Conditions (identified by the row SQN) as a causal factor.

Table 13. Conditional Proportion Matrix of Pairwise Combinations of Second-Order HFACS-ME categories for Mishaps FY90 – FY99.

	ORG	SQN	MED	CRW	RDY	ENV	EQP	WRK	ERR	VIO
ORG		0.346	0.160	0.279	0.429	0.167	0.600	0.000	0.360	0.321
SQN	0.444		0.440	**0.651**	**0.714**	0.333	0.600	0.000	0.517	0.634
MED	0.028	0.060		0.163	0.000	0.167	0.100	0.000	0.035	0.061
CRW	0.085	0.154	0.280		0.000	0.000	0.200	0.000	0.157	0.168
RDY	0.021	0.027	0.000	0.000		0.167	0.100	0.000	0.029	0.015
ENV	0.007	0.011	0.040	0.000	0.143		0.000	0.500	0.006	0.008
EQP	0.042	0.033	0.040	0.047	0.143	0.000		0.000	0.029	0.031
WRK	0.000	0.000	0.000	0.000	0.000	0.167	0.000		0.000	0.000
ERR	0.437	0.489	0.240	0.628	**0.714**	0.167	0.500	0.000		0.366
VIO	0.296	0.456	0.320	0.512	0.286	0.167	0.400	0.000	0.279	

Any value in the matrix reported at 65 percent or above is considered to be significant enough to warrant further analysis. Adopting this delineating criterion reveals that three combinations are considered to be significant. Given that Maintainer Readiness (RDY) is cited in an MRM, it is particularly likely that either Squadron Supervisory Conditions (SQN) or Maintainer Error (ERR) are also reported as causal factors. Similarly, given that Maintainer Crew Coordination (CRW) is cited as a causal factor in an MRM, then it is quite likely that Squadron Supervisory Conditions (SQN) will also be cited.

V. SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

A. SUMMARY

The US government's unwavering requirements upon the military demand high levels of operational readiness, equipment availability, and personnel training, all within a climate of reduced budgets and downsizing. The seemingly inequitable notion that most public sector organizations are being expected to do more with less is today's reality. Asset preservation is of paramount importance as funding is simply not available to provide replacements in the short-term. Naval Aviation mishaps impact mission capability, operational readiness, and costs, not to mention the human cost. In line with this, it is regarded that through the reduction of avoidable human errors that contribute to mishaps, existing Naval Aviation assets will be preserved and the associated repair or replacement costs will be avoided. To achieve this, the role human error plays in aviation mishaps must be identified, and appropriate intervention strategies developed and programs aimed at reducing the causes of these errors, implemented. Contemporary accident causation theories suggest that accidents are the result of a complex combination of errors. The question of where to target intervention strategies is the key aspect in effectively combating human error.

Substantial advances have been made in the area of aircrew error reduction; it is now time for similar bounds to be made in the area of maintainer error reduction. This study has confronted this dilemma and has again validated the use of the Human Factors Analysis and Classification System Maintenance Extension (HFACS-ME) taxonomy as being sufficient for the classification of human factors contributing to maintenance-

related mishaps (MRMs). Should such a framework be adopted for the investigation and reporting of mishaps, then a much clearer picture will be given of the full impact of contributing human factors. From this basis, mishap prevention programs should be tailored to intervene and prevent active failures from causing MRMs or for latent conditions from becoming the catalyst for them.

B. CONCLUSIONS

This study concludes that the modified HFACS-ME taxonomy provides an adequate framework for the classification of MRM causal factors. The newly developed stochastic models show that the variable Poisson process model provides a satisfactorily robust, yet straightforward model for predicting future mishaps. The trend analysis of the causal factors of MRMs revealed that there is a significant relationship between the causal dimensions of Squadron Supervisory Conditions (SQN) and Maintainer Violation (VIO), enough to warrant the suggestion that the correlation of these aspects be further investigated.

The words of Box (1978) have been a constant companion during the course of this study, "All models are wrong. Some models are useful." To this end the models developed in this study are presented as simply a guide to permit the exploration of a possible future state. The extrapolation of current trends observed in the data may give some valuable insights into the future environment surrounding the modeled data. While historical data might not be able to accurately forecast future events, the outlook that it provides gives a starting point from which to hypothesize about probable outcomes.

The development of models predicting future MRMs highlighted one of the serious pitfalls of data aggregation. While suitable models were developed and fitted to Class A, B and C mishaps, as well as to Flight, Flight-Related, and Aircraft-Ground mishaps, the rates at which these models are declining differ significantly enough to cause difficulties in developing a single model for total MRMs. Accordingly, scant regard should be paid to such aggregated models; attention instead should be focused on prediction models derived from more homogeneous data sets.

It was observed that very few mishaps recorded contributing factors relating to Working Conditions. While it is considered that Working Conditions is a valid classification in the HFACS-ME taxonomy, it is felt that existing investigation and reporting methodologies do not give such factors sufficient credence so as to warrant their inclusion in the mishap investigation report. It is quite conceivable that these aspects do contribute to mishaps; however, it is only by promoting the awareness of such aspects through employing appropriate investigating and reporting methodologies, that these aspects will be effectively accounted for.

C. RECOMMENDATIONS

Present mishap investigation procedures outlined in OPNAV Instruction 3750.6Q do not incorporate specific guidance in addressing the wide variety of human factors that can contribute to the cause of MRMs. Through incorporating a taxonomy similar to that embodied in HFACS-ME, the investigation of MRMs will be more rigorous and areas for intervention will be more readily identified and prioritized. Accordingly, it is recommended that the Naval Safety Center and Naval Air Systems Command instigate

action to revise current mishap investigation procedures to incorporate a theoretical framework, such as the HFACS-ME taxonomy, that fosters the thorough examination of all pertinent human factors. This action would make the reporting mechanism more complete, as well as more sensitive to multiple causes of the mishap. Subsequent analyses of this information would be more refined than present studies and more closely model the true causes of MRMs.

Analysis of the various causal factors attributed to MRMs has revealed significant relationships between certain classifications. It is recommended that the Naval Safety Center and Naval Air Systems Command commission further research efforts to identify correlations between the causal dimensions with the view to understand these interactions. It is anticipated that such a study would address questions such as whether one factor precipitates the other, or whether implementing intervention strategies aimed at addressing one dimension would invariably reduce the occurrence of the other. Through comprehension of such correlations, intervention strategies could be more effectively and efficiently employed. (Postscript annotation: The Naval Safety Center, as a result of this and previous studies, has elected to incorporate HFACS-ME into OPNAV 3750.R, the new Naval Aviation Safety program instruction.)

APPENDIX A. ORIGINAL HFACS-ME CLASSIFICATION CODES

The following descriptions are taken from Schmidt, Schmorrow & Hardee (1997) and are used with permission.

Latent **Supervisory Conditions** that can contribute to an active failure includes both unforeseen and squadron.

Examples of **unforseen supervisory** conditions include:

- An engine that falls off of a stand during a change-out evolution due to an unforeseen hazard of a high seas state (Hazardous Operation)
- A manual omits a step in a maintenance procedure, such as leaving out an o-ring that causes a fuel leak (Inadequate Documentation)
- The poor layout of system components that do not permit direct observation of maintenance being performed (Inadequate Design)

Examples of **squadron supervisory** conditions include:

- A supervisor who does not ensure that maintenance personnel are wearing required personal protective gear (Inadequate Supervision)
- A supervisor who directs a maintainer to perform a task without considering risks, such as driving a truck through a hangar (Inappropriate Operations)
- A supervisor who neglects to correct maintainers who routinely bend the rules when they perform a common task (Uncorrected problem)
- A supervisor who willfully orders a maintainer to wash an aircraft without proper safety gear (Supervisory Violation)

Latent **Maintainer Conditions** that can contribute to an active failure include medical, crew coordination, and readiness.

Examples of maintainer **medical** conditions include:

- A maintainer who has a marital problem and cannot focus on a maintenance action (Mental State)
- A maintainer who worked for 20 hours straight and suffers from fatigue (Physical State)
- A maintainer who is short can not visually inspect aircraft before it is launched (Physical/Mental Limitation).

Examples of maintainer **crew coordination** conditions include:

- A maintainer who leads a taxiing aircraft into another due to improper hand signals (Communication)
- A maintainer who performs a task, not in accordance with standard procedures, because the maintainer was overly submissive to a superior (Assertiveness)
- A maintainer who downplays a downing discrepancy to meet the flight schedule (Adaptability/Flexibility)

Examples of maintainer **readiness** conditions include:

- A maintainer who is working on an aircraft skipped the requisite OJT evolution (Preparation/Training)
- A maintainer who engages in a procedure that they have not been qualified to perform (Qualification/Certification)
- A maintainer who is intoxicated on the job (Violation)

Latent **Working Conditions** that can contribute to an active failure include environmental, equipment, and workspace.

Examples of **environmental** working conditions include:

- A maintainer who is working at night on the flightline does not see a tool he left behind (Lighting/Light)
- A maintainer who is securing an aircraft in a driving rain fails to properly attach the chains (Weather/Exposure)
- A maintainer who is working on a pitching deck falls from the aircraft (Environmental Hazard)

Examples of **equipment** working conditions include:

- A maintainer who is using a defective test set does not pre-check it before troubleshooting (Damaged)
- A maintainer who starts working on landing gear without a jack because all in use (Unavailable)
- A maintainer who uses an old manual because a CD-ROM reader is not available (Dated/Uncertified)

Examples of **workspace** working conditions include:

- A maintainer who is working in a hangar bay cannot properly position the maintenance stand (Confining)
- A maintainer who is spotting an aircraft with his view obscured by catapult steam (Obstructed)
- A maintainer who is unable to perform a corrosion inspection that is beyond his reach (Inaccessible)

Maintainer Acts are active failures, which directly or indirectly cause mishaps, or lead to Latent Maintenance Condition, they include errors and violations.

Examples of **errors** in maintainer acts include:

- A maintainer who misses a hand signal and backs a forklift into an aircraft (Attention)
- A maintainer who is very familiar with a procedure may reverse steps in a sequence (Memory)
- A maintainer who inflates an aircraft tire to a pressure required by a different aircraft (Knowledge/Rule)
- A maintainer who roughly handles a delicate engine valve causing damage (Skill)

Examples of **violations** in maintainer acts include:

- A maintainer who engages in practices, condoned by management, that bend the rules (Routine)
- A maintainer who strays from accepted procedures to save time, bending a rule (Infraction)
- A maintainer who willfully breaks standing rules disregarding the consequences (Exceptional)

APPENDIX B. MODIFIED HFACS-ME CLASSIFICATIONS

Table B1. HFACS-ME Taxonomy

First Order	Second Order	Third Order
Supervisory Conditions	Corporate	Hazardous Operations Inadequate Documentation Inadequate Design Inadequate Processes Inadequate Resources
	Local	Inadequate Supervision Inappropriate Operations Uncorrected Problem Supervisory Misconduct
Maintainer Conditions	Medical	Mental State Physical State Limitation
	Crew Coordination	Communication Assertiveness Adaptability/Flexibility
	Readiness	Training/Preparation Certification/Qualification Infringement
Working Conditions	Environment	Lighting/Light Weather/Exposure Environmental Hazards
	Equipment	Damaged Unavailable Dated/Uncertified
	Workspace	Confining Obstructed Inaccessible
Maintainer Acts	Error	Attention Memory Knowledge/Rule Based Skill Based Judgment/Decision-Making
	Violation	Routine Infraction Flagrant Sabotage

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APPENDIX C. MEDART SOFTWARE TOOL

A. OVERVIEW

To support the data purification effort, Microsoft Access 97 was used to develop a prototype software tool – the Maintenance Error Data Analysis and Reporting Tool (MEDART). The purpose of MEDART is to provide a readily accessible mishap reporting and analysis tool for maintenance-related safety personnel. While Access 97 provides rudimentary functionality for data analysis and display, it lacks a degree of flexibility and is not quite as user-friendly or aesthetically pleasing as it could be. As such a custom-built application, using Visual Basic for Applications (VBA) programming code, was developed to provide a much more effective interface from the user's perspective.

B. FUNCTIONALITY

Although the MEDART software tool was developed solely as a prototype version to support data purification, a secondary aim was to display the types of feedback the users could expect to see when using such a tool. Accordingly, its functionality is presently somewhat limited. The basic functionality of MEDART is divided into four main areas: data entry, database querying, database reporting, and data graphing (see Figure C1). Some of these areas were then broken down into other, distinct sub-areas. It is suggested that additional functionality such as an improved and expanded reporting facility, greater freedom to select multiple data items within each criterion of a query, and greater flexibility within the graphing module, should be incorporated in future versions.

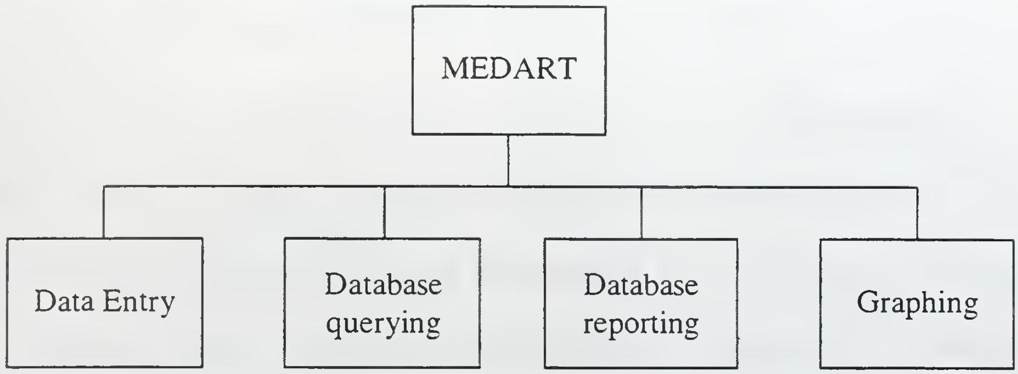


Figure C1. Flow Chart Depicting Basic MEDART Functionality.

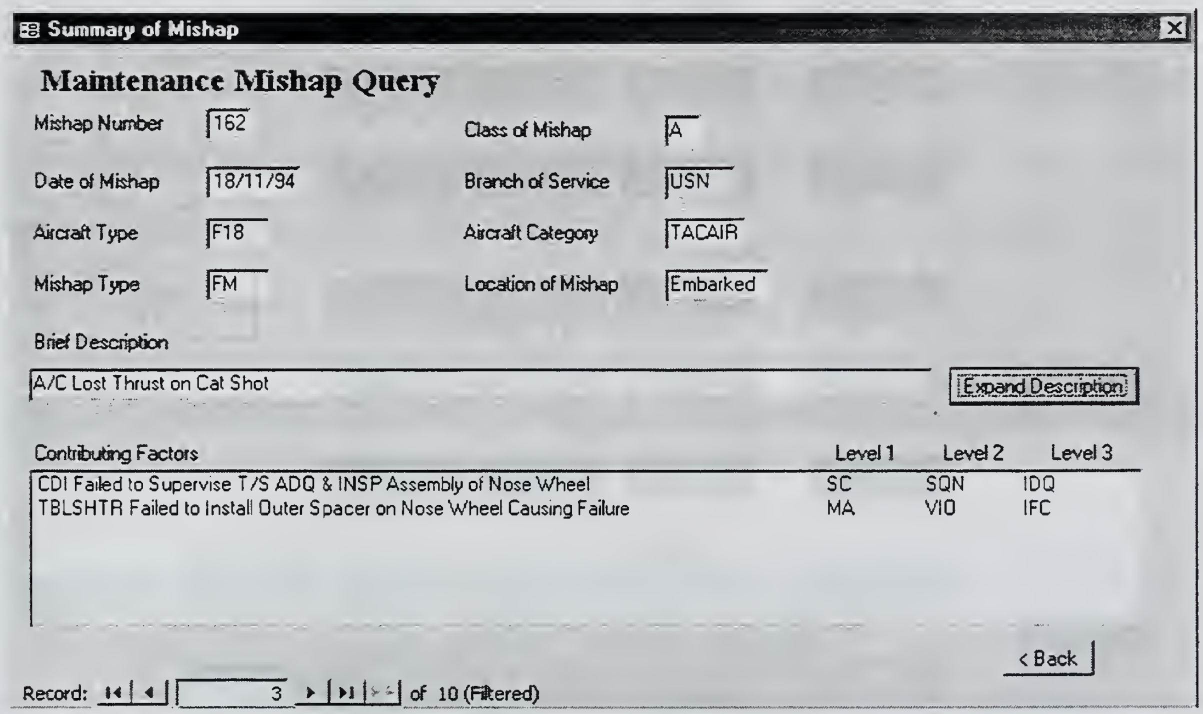
1. Data Entry

The data entry module is rather elementary; however, where possible the user is assisted in entering data through the provision of pull-down boxes, complete with suggested data values. This method significant reduces the amount of typing the user is required to do, as well as reducing the potential for errors through incorrectly entered data. An edit facility was not incorporated as it was felt that allowing users the ability to edit existing data might cause the inadvertent and unintentional modification of stored data. Should the user have a specific need to modify data in the database, then a user with a rudimentary knowledge of Access 97 would be able to easily address this need by directly manipulating the underlying tables in MEDART.

2. Database querying

There are two basic methods of querying the database: filtering by selected HFACS-ME category, or by identifying other pertinent aspects of the mishap, such as mishap class, date, aircraft model, and so on. Both these methods display a subset of

mishaps, one by one, that meet the selection criteria. A count of the number of MRMs that satisfy the criteria is also presented to the user. When utilising the latter method of database query, the user is able to select multiple criteria with which to filter the information in the database. Figure C2 shows the Maintenance Mishap Query screen, in this instance the selection criteria has been set so as to only display those Class A MRMs that were also F/A-18 Flight mishaps. The aqua blue background of the class, aircraft type and mishap type data fields in Figure C2 signifies that these fields have been specified in the filtering criteria (note: colors are not depicted in this appendix section).



FigureC2. Maintenance Mishap Query Screen.

3. Database Reporting

Due to time constraints in the development of this application, this particular area of functionality was not expanded. A number of basic reports are available to the user;

these range from the distribution of all MRMs by HFACS-ME category (see Figure C3), all MRMs with associated factors, to the distribution of MRMs by service. Each report is formatted on the screen to represent a printed page, hence, the production of hard-copy reports is as simple as clicking a button.

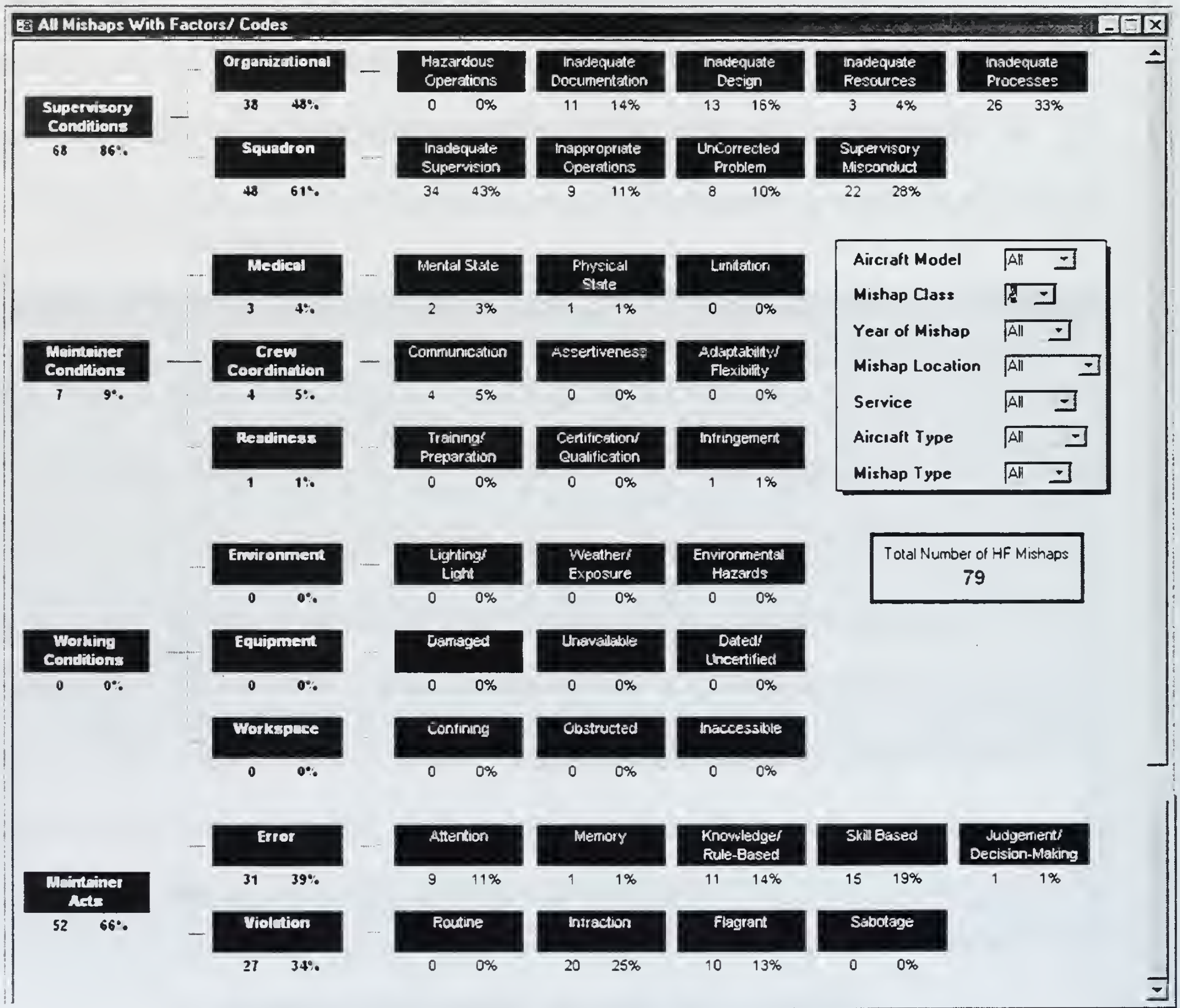


Figure C3. Screen Query - Distribution of MRMs by HFACS-ME Code.

4. Data Graphing

Custom VBA code was written to interface with Microsoft Access 97's charting facility, which in turn is a subset of Excel 97's charting functionality. Predefined graphs are available to the novice user that display aspects such as mishap percentage by aircraft model, the location of MRM by aircraft model, and the distribution of class of MRM by aircraft model. For the more adventurous user, a custom two-dimensional graph can be created by selecting mishap criteria for the X and Y axes, then selecting certain values for each criterion to then be displayed. Figure C4 shows the graph created using the MEDART Expert Graph function, where all Class A mishaps for selected aircraft during the period CY90- CY99 are given. Giving the more proficient user access to the Expert Graph function permits users to create graphs the cater to their specific needs. These graphs can then be copied into other software packages such as Word and PowerPoint, and used in reports and presentations to highlight aspects of mishap occurrence.

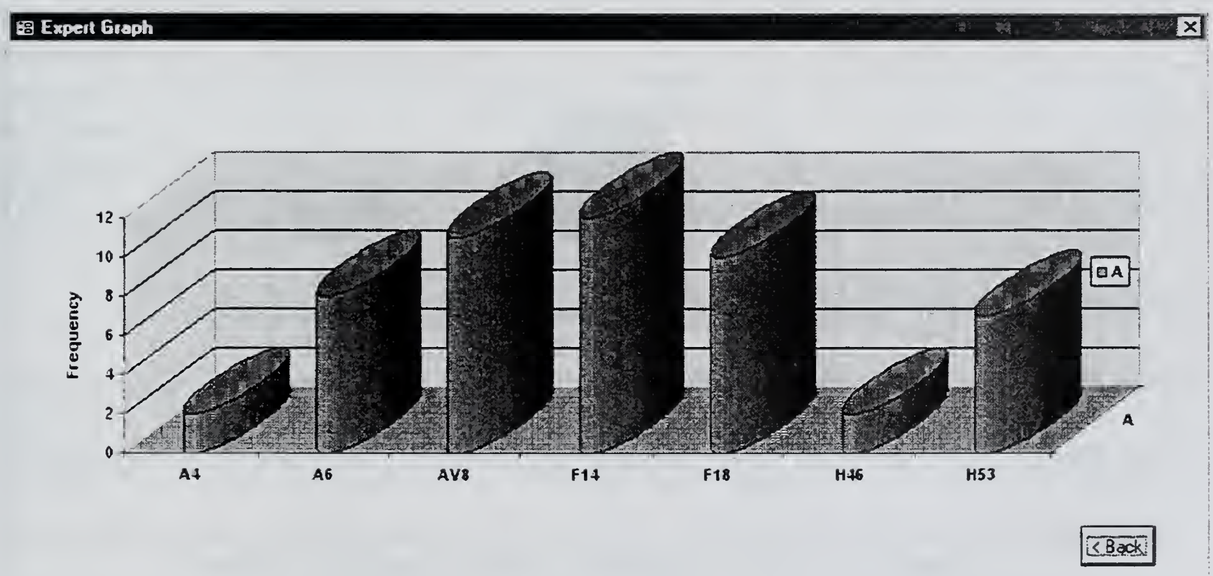


Figure C4. Class A MRMs (CY90 – CY99) For Selected Aircraft Models.

C. MEDART OUTPUT

Whether by using the built-in reports, charts or tables to display information, or by exporting the data to other software packages to display the information in a slightly different form, a significant amount of information about the underlying data can be gleaned by the user. Figure C5 shows the percentage of Class A mishaps for CY90-99 by mishap type, a graph that is one of the built in options presented to users under the MEDART graphing functionality. This particular pie chart shows that an overwhelming majority of Class A MRMs were flight mishaps (FM). This is not overly surprising when considering the definition of a Class A MRM (i.e. significant damage/loss with the intent for flight) and the greater associated probability of catastrophe in the event of a mishap. Despite this knowledge, it is regarded that this information would almost certainly indicate that this is an area to be targeted for further investigation and the identification of intervention strategies.

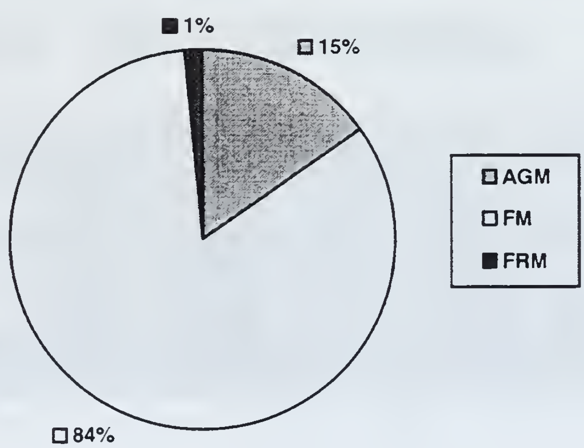


Figure C5. Class A MRMs By MRM Type for CY90-99.

The means of providing information to the user is not limited to just those functions provided within the MEDART application. Almost all US military personnel have access to the Microsoft Office suite of applications. The information displayed in Table C1 was derived from mishap data exported from Microsoft Access 97 into a Microsoft Excel 97 spreadsheet. Within Excel, VBA macros were written to summarize the MRMs. This spreadsheet data was then copied into Microsoft Word 97 and reshaped into the table as presented. With a minimum of effort and an introductory knowledge of VBA and the Microsoft Office suite, similar results could be obtained by any user.

Table C1. Class A MRMs by CY.

	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	Total
January	3	2	2	0	0	1	0	0	0	0	8
February	0	0	0	0	0	0	1	0	0	0	1
March	1	0	2	2	0	1	0	0	0	1	7
April	1	0	1	1	0	0	0	0	3	2	8
May	1	1	1	0	1	0	1	1	0	0	6
June	3	0	1	2	1	0	0	0	0	1	8
July	0	3	2	2	0	0	0	0	1	1	9
August	1	2	0	0	1	1	0	1	1	0	7
September	0	0	0	0	1	0	1	0	0	0	2
October	0	2	2	0	1	1	2	1	0	0	9
November	1	0	1	1	1	0	0	1	0	0	5
December	2	0	0	0	0	0	0	0	0	0	2
Total	**13**	**10**	**12**	**8**	**6**	**4**	**5**	**4**	**5**	**5**	**72**

In a similar manner, the graphs depicted in Figures C6, C7 and C8 were created from mishap data exported as an Excel 97 spreadsheet. In Excel, the MRMs were summarized into tables that calculated the frequency with which each HFACS-ME code occurred in Class A MRMs from CY90 to CY99. The three graphs depict each the three hierarchical orders of HFACS-ME codes respectively. Figure C6 shows the First Order

HFACS-ME categories and again it can be seen that a significant proportion of Class A MRMs are flight mishaps.

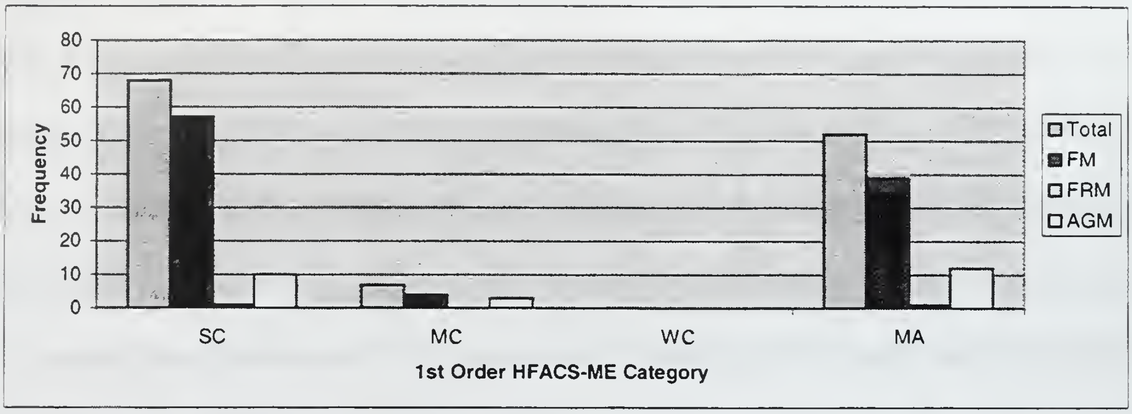


Figure C6. Class A MRMs (CY90-99) by First Order HFACS-ME Categories.

As a result of examining Figure C7, a greater level of detail can be gleaned about the distribution of causal factors for Class A MRMs. Predictably, the causal dimensions of Organisational (ORG) and Squadron (SQN), which pertain to the superior Supervisory Condition category, and Error (ERR) and Violation (VIO), which pertain to the superior Maintainer Acts category, are the most frequently observed. The additional information presented by this graph (over that presented in Figure C6) suggests that local (or Squadron) supervisory aspects and unintentional maintainer errors are the most prevalent types of errors in each of their corresponding first order categories.

While difficult to read in the scale presented, Figure C8 gives an even greater level of definition to the causal factors of Class A MRMs in CY90-99. The third order causal dimensions of inadequate supervision, inappropriate processes, supervisory

misconduct, and infraction of regulations were each attributed as causal factors in 20 or more of the 79 Class A MRMs during the period.

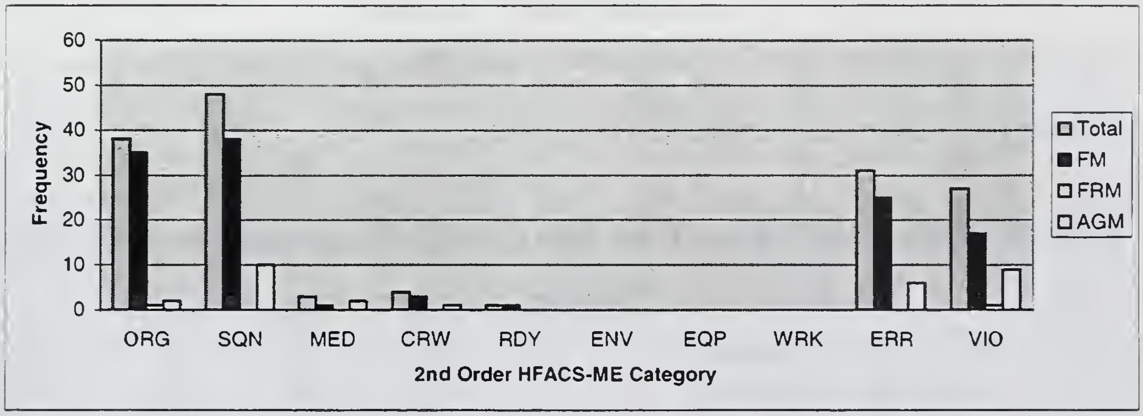


Figure C7. Class A MRMs (CY90-99) by Second Order HFACS-ME Categories.

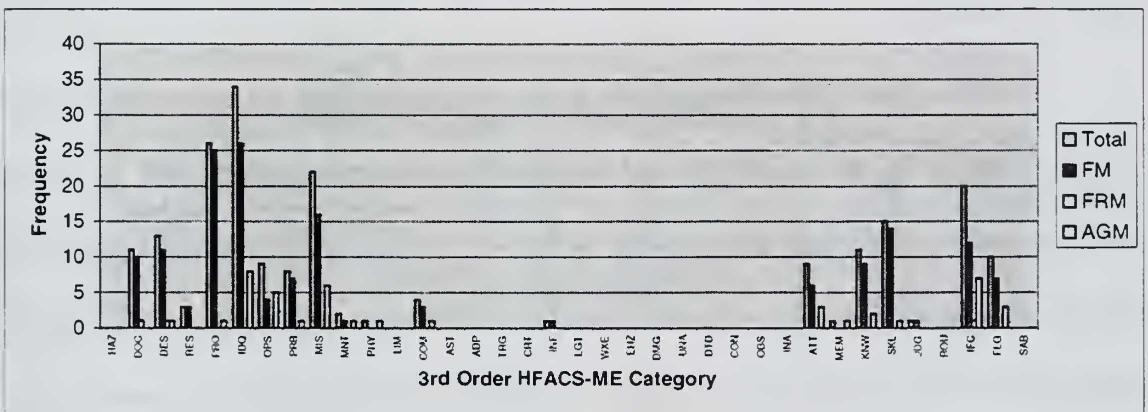


Figure C8. Class A MRMs (CY90-99) by Third Order HFACS-ME Categories.

The data exported to the Excel spreadsheet was also summarized in a manner to produce Table C2. This table combines mishap type with the four first order HFACS-ME classifications. Other than the total number of MRMs that reported an instance of each of the four codes, the percentage breakdown of HFACS-ME codes across mishap type is also given. This shows that during the period CY90 - CY99, 84 percent of Class A

MRMs that reported Supervisory Conditions as a causal factor were also flight mishaps. A figure of similar magnitude is associated with Maintainer Acts and flight mishaps. This could quite possibly be an area for concern; however, intuition suggests that there is a propensity to point blame in catastrophic accidents, particularly at the person who performed the maintenance and his/her supervisors.

Table C2. Class A MRM First Order HFACS-ME Classifications By Mishap Type

	TOTAL	FM	FRM	AGM
Supervisory Conditions	68	84%	1%	15%
Maintainer Conditions	7	57%	0%	43%
Working Conditions	0	NA	NA	NA
Maintainer Acts	52	75%	2%	23%

D. SUMMARY

The prototype MEDART application has shown that such a tool can be invaluable in providing the both the novice and intermediate computer users with a powerful instrument for the reporting and analysis of MRMs. These users can readily generate the myriad of reports and displays required to gain a sufficient appreciation of the trends and associations within mishap data. While the prototype version of this software has its limitations, it is anticipated that a commercially-developed working version would offer a greater degree of flexibility and usability to aviation maintenance-related safety personnel.

APPENDIX D. MONTHLY SUMMARY OF MRMS BY TYPE AND CLASS FOR FY90-FY99

Table D1. Flight MRMs by FY.

	90	91	92	93	94	95	96	97	98	99	Total
October	0	1	3	5	1	2	1	4	1	0	18
November	2	5	1	1	2	1	1	0	3	0	16
December	2	1	0	2	2	1	1	0	1	0	10
January	5	9	2	2	4	2	1	2	0	1	28
February	3	2	1	1	1	0	3	0	1	1	13
March	6	1	3	2	2	4	2	1	3	4	28
April	2	3	4	3	0	0	0	1	4	1	18
May	2	2	3	1	2	2	2	2	2	1	19
June	4	2	4	4	5	1	1	1	2	1	25
July	1	6	1	1	3	0	0	2	2	2	18
August	2	7	0	1	4	2	2	1	5	4	28
September	1	1	1	1	1	0	1	1	2	2	11
Total	30	40	23	24	27	15	15	15	26	17	**232**

Table D2. Flight-Related MRMs by FY.

	90	91	92	93	94	95	96	97	98	99	Total
October	1	0	0	1	2	0	0	0	1	0	5
November	1	2	1	0	0	0	0	0	0	0	4
December	0	2	0	1	0	0	0	1	0	0	4
January	0	2	1	0	0	0	1	1	0	0	5
February	0	1	0	0	0	1	1	0	0	0	3
March	3	0	1	0	2	0	0	0	0	0	6
April	0	0	0	0	1	0	0	0	0	1	2
May	1	0	1	1	0	0	0	0	0	0	3
June	2	1	1	1	0	0	1	0	1	1	8
July	0	0	1	0	0	0	0	0	0	1	2
August	1	0	1	0	0	0	0	0	0	1	3
September	1	1	1	0	1	0	1	0	1	0	6
Total	10	9	8	4	6	1	4	2	3	4	**51**

Table D3. Aircraft-Ground MRMs by FY.

	90	91	92	93	94	95	96	97	98	99	Total
October	3	3	3	4	3	4	4	3	0	1	28
November	3	3	4	0	4	1	1	0	1	1	18
December	2	3	2	3	0	3	0	2	2	3	20
January	4	4	5	3	5	3	4	0	1	1	30
February	5	2	1	4	4	0	4	3	3	0	26
March	4	4	6	3	2	4	2	1	0	5	31
April	1	3	1	2	3	2	0	3	2	2	19
May	5	4	7	1	2	2	2	3	1	0	27
June	3	2	1	6	6	3	0	2	4	2	29
July	4	6	6	7	5	2	2	1	3	3	39
August	3	7	2	4	1	1	1	1	5	0	25
September	3	4	3	5	1	2	1	1	2	2	24
Total	40	45	41	42	36	27	21	20	24	20	**316**

Table D4. Class A MRMs by FY.

	90	91	92	93	94	95	96	97	98	99	Total
October	0	0	2	2	0	1	1	2	1	0	9
November	2	1	0	1	1	1	0	0	1	0	7
December	1	2	0	0	0	0	0	0	0	0	3
January	3	2	2	0	0	1	0	0	0	0	8
February	0	0	0	0	0	0	1	0	0	0	1
March	1	0	2	2	0	1	0	0	0	1	7
April	1	0	1	1	0	0	0	0	3	2	8
May	1	1	0	0	1	0	1	1	0	0	5
June	3	0	1	2	1	0	0	0	0	1	8
July	0	3	2	2	0	0	0	0	1	1	9
August	1	2	0	0	1	1	0	1	1	0	7
September	0	0	0	0	1	0	1	0	0	0	2
Total	13	11	10	10	5	5	4	4	7	5	**74**

Table D5. Class B MRMs by FY.

	90	91	92	93	94	95	96	97	98	99	Total
October	0	0	1	1	0	1	1	1	0	0	5
November	1	2	1	0	0	0	0	0	0	0	4
December	1	0	0	0	0	1	0	2	0	0	4
January	0	1	1	0	0	1	2	0	0	0	5
February	0	1	0	0	0	1	0	0	1	0	3
March	0	0	0	0	1	2	0	1	1	1	6
April	0	2	0	2	0	1	0	1	1	0	7
May	1	2	2	0	0	0	0	1	0	0	6
June	1	1	0	1	1	0	0	1	0	1	6
July	1	0	0	0	2	0	0	0	1	0	4
August	1	3	1	2	0	0	0	0	1	1	9
September	1	2	1	0	0	0	1	1	0	1	7
Total	7	14	7	6	4	7	4	8	5	4	**66**

Table D6. Class C MRMs by FY.

	90	91	92	93	94	95	96	97	98	99	Total
October	4	4	3	7	6	4	3	4	1	1	37
November	3	7	5	0	5	1	2	0	3	1	27
December	2	4	2	6	2	3	1	1	3	3	27
January	6	12	5	5	9	3	4	3	1	2	50
February	8	4	2	5	5	0	7	3	3	1	38
March	12	5	8	3	5	5	4	1	2	7	52
April	2	4	4	2	4	1	0	3	2	2	24
May	6	3	9	3	3	4	3	3	3	1	38
June	5	4	5	8	9	4	2	2	7	2	48
July	4	9	6	6	6	2	2	3	3	5	46
August	4	9	2	3	4	2	3	1	8	4	40
September	4	4	4	6	2	2	1	1	5	3	32
Total	60	69	55	54	60	31	32	25	41	32	**459**

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APPENDIX E. S-PLUS USER-DEFINED FUNCTION COMPUTER CODE

DRR.FUNC

```
function(obj)
{
#
# drr.func: Do the "double-root" chi-squared test on the object in
# "obj", the glm.  Written by S.E. Buttrey.
#
# First extract the y's. Then get the predicted lambdas from predict()
#
      y <- obj$y
      lambda <- predict(obj, type = "response") #
#
# Compute the "double roots".
#
      drr <- sqrt(y) + sqrt(y + 1) - sqrt(4 * lambda + 1)    #
#
# Under the null hypothesis, these things are roughly Normal, which
# means the sum of their squares is roughly Chi-squared, with df = n-2
# (losing one for the slope and one for the intercept).
#
      stat <- sum(drr^2)
      p.val <- 1 - pchisq(sum(drr^2), df = length(y) - 2)
      return(c(stat = stat, p.value = p.val, df = length(y) - 2))
}
```

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APPENDIX F. FITTED VARIABLE POISSON PROCESS MODELS FOR MRM TYPE AND CLASS FOR THE PERIOD FY90 – FY99

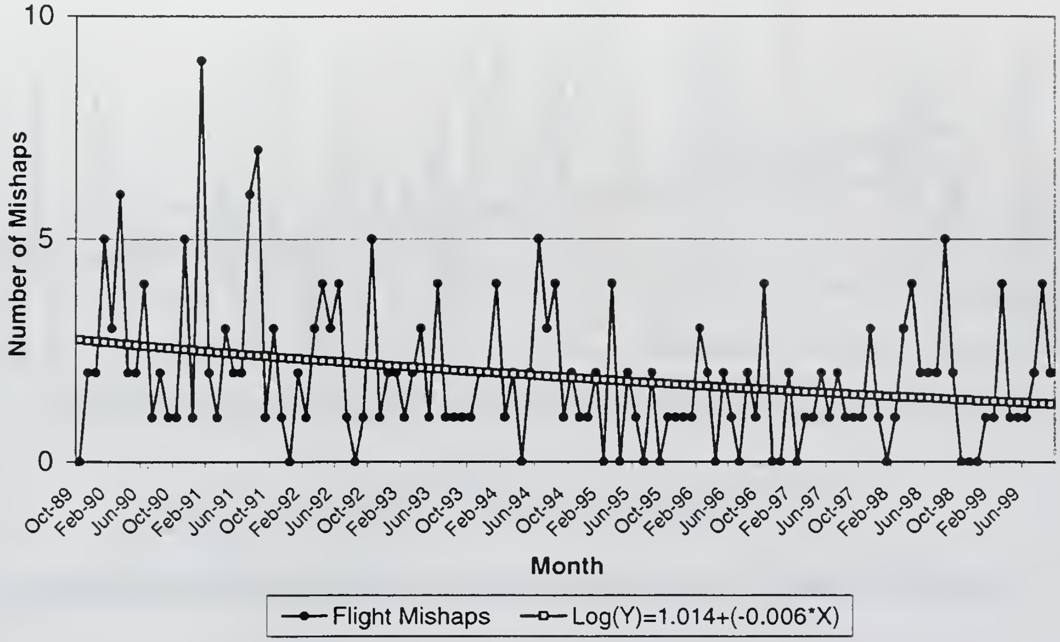

Figure F1. Variable Poisson Process Model for Flight MRMs.

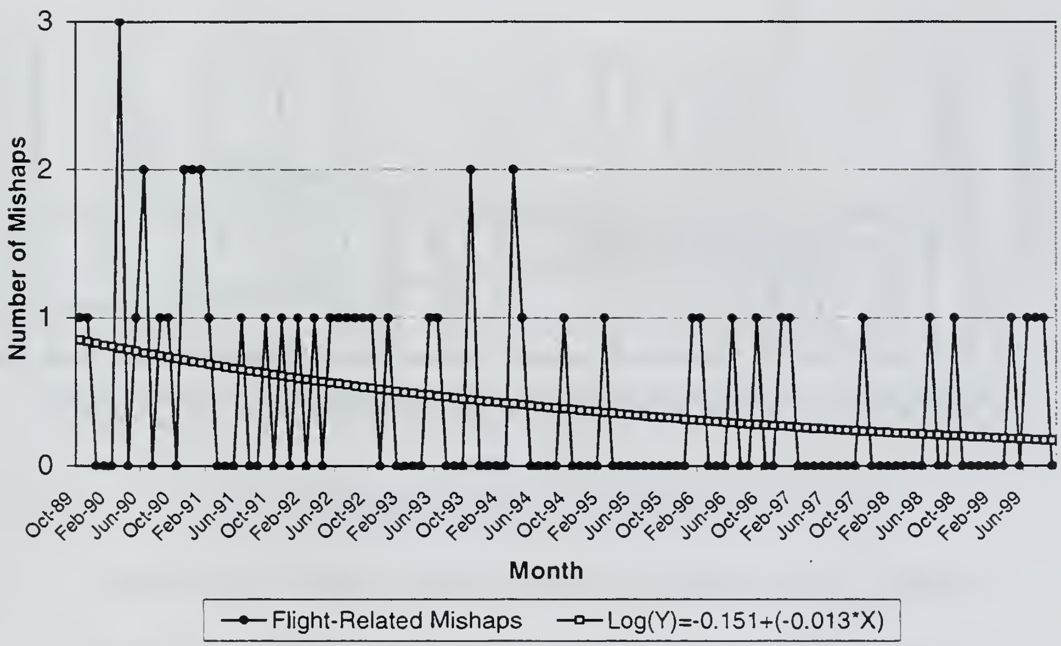

Figure F2. Variable Poisson Process Model for Flight-Related MRMs.

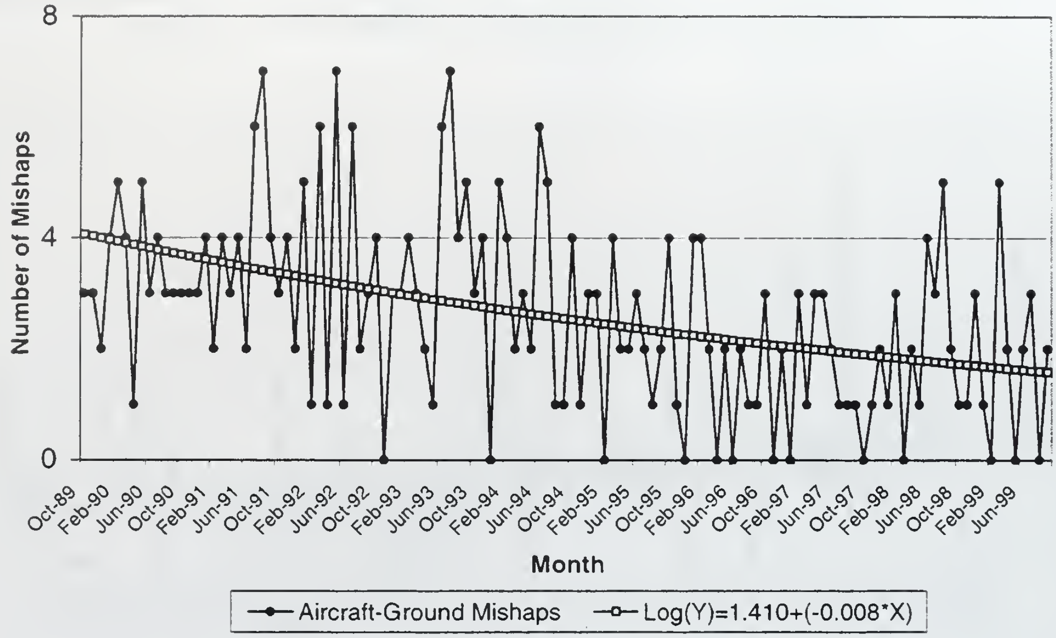

Figure F3. Variable Poisson Process Model for Aircraft-Ground MRMs.

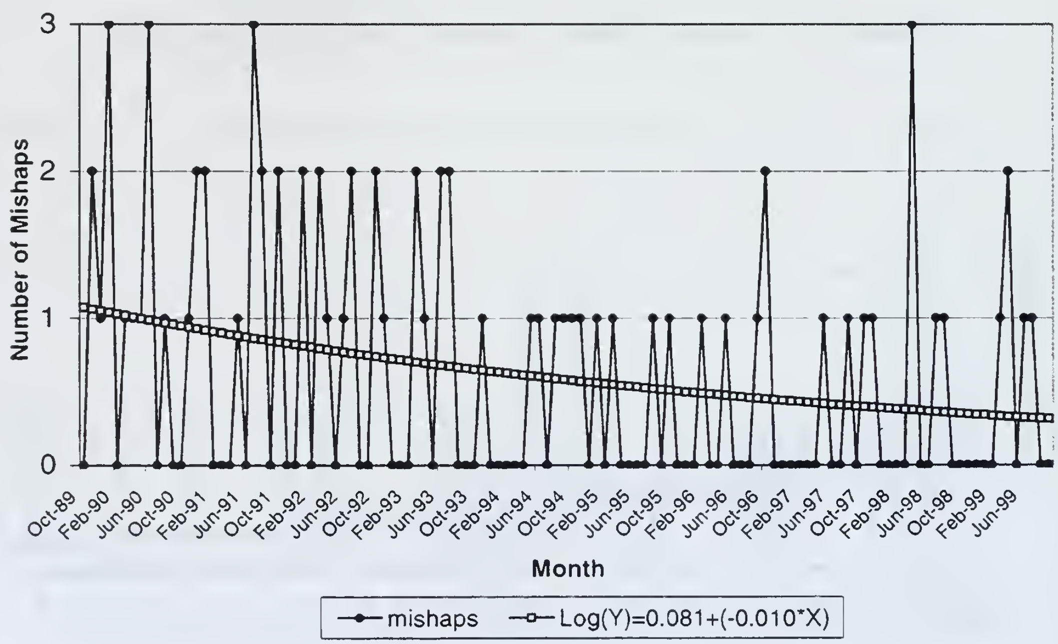

Figure F4. Variable Poisson Process Model for Class A MRMs.

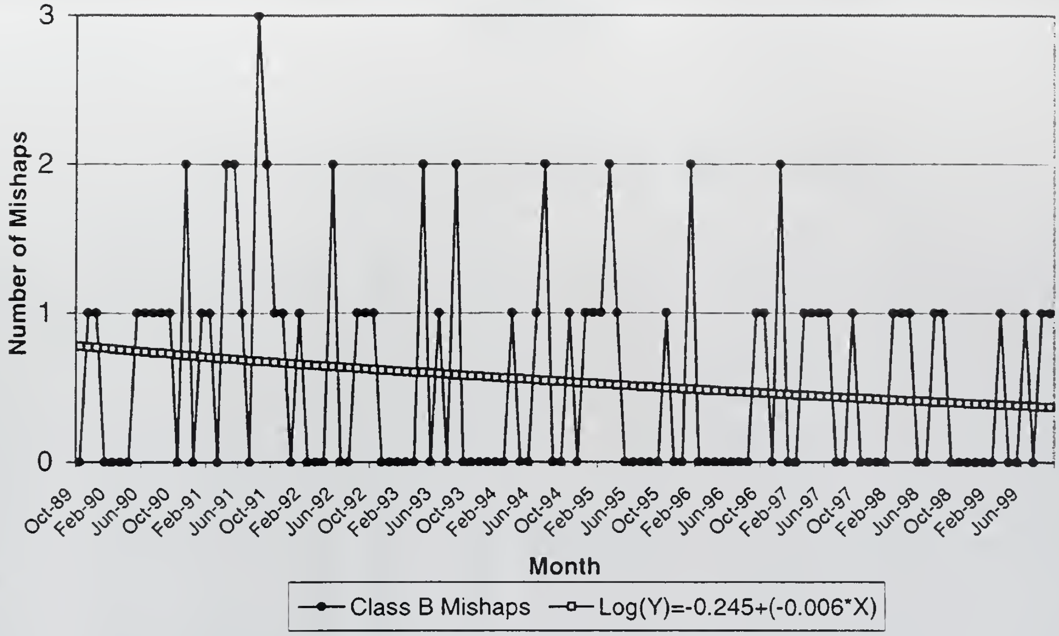

Figure F5. Variable Poisson Process Model for Class B MRMs.

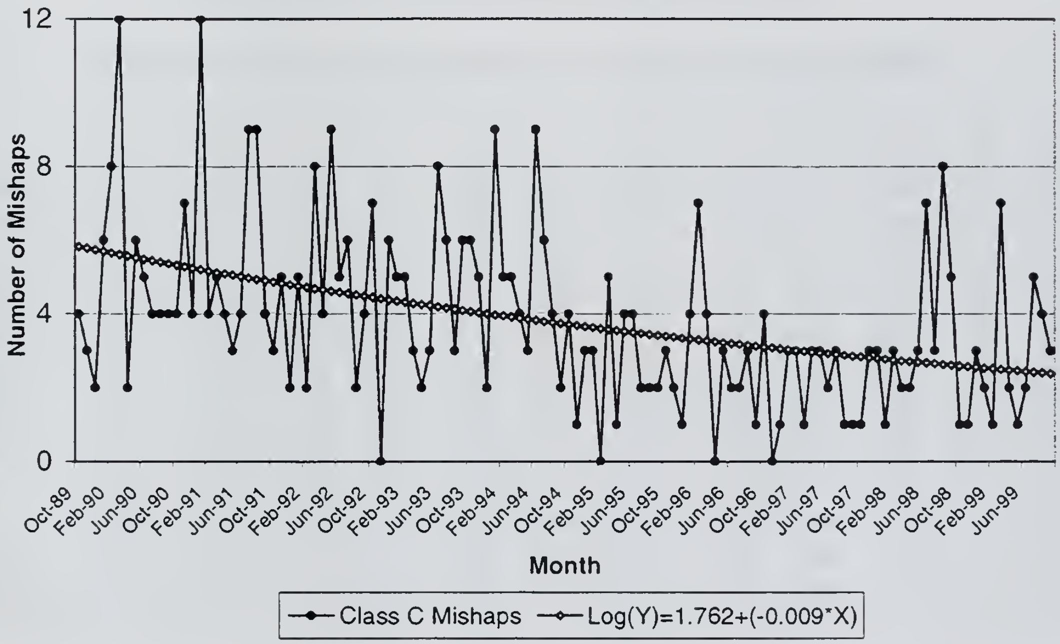

Figure F6. Variable Poisson Process Model for Class C MRMs.

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APPENDIX G. PROBABILITY TABLES FOR THE OCCURRENCE OF MRMS FOR FY00

Table G1. Flight MRM Probability Table for FY00.

	$\hat{\lambda}_t$	0	1	2	3	4	5	6	7	8	9	10
October	1.29	0.28	0.36	0.23	0.10	0.03	0.01	0.00	0.00	0.00	0.00	0.00
November	1.29	0.28	0.36	0.23	0.10	0.03	0.01	0.00	0.00	0.00	0.00	0.00
December	1.28	0.28	0.36	0.23	0.10	0.03	0.01	0.00	0.00	0.00	0.00	0.00
January	1.27	0.28	0.36	0.23	0.10	0.03	0.01	0.00	0.00	0.00	0.00	0.00
February	1.26	0.28	0.36	0.23	0.09	0.03	0.01	0.00	0.00	0.00	0.00	0.00
March	1.25	0.29	0.36	0.22	0.09	0.03	0.01	0.00	0.00	0.00	0.00	0.00
April	1.25	0.29	0.36	0.22	0.09	0.03	0.01	0.00	0.00	0.00	0.00	0.00
May	1.24	0.29	0.36	0.22	0.09	0.03	0.01	0.00	0.00	0.00	0.00	0.00
June	1.23	0.29	0.36	0.22	0.09	0.03	0.01	0.00	0.00	0.00	0.00	0.00
July	1.22	0.30	0.36	0.22	0.09	0.03	0.01	0.00	0.00	0.00	0.00	0.00
August	1.22	0.30	0.36	0.22	0.09	0.03	0.01	0.00	0.00	0.00	0.00	0.00
September	1.21	0.30	0.36	0.22	0.09	0.03	0.01	0.00	0.00	0.00	0.00	0.00

Table G2. Flight-Related MRM Probability Table for FY00.

	$\hat{\lambda}_t$	0	1	2	3	4	5	6	7	8	9	10
October	0.17	0.84	0.14	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
November	0.17	0.84	0.14	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
December	0.17	0.84	0.14	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
January	0.16	0.85	0.14	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
February	0.16	0.85	0.14	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
March	0.16	0.85	0.14	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
April	0.16	0.85	0.14	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
May	0.15	0.86	0.13	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
June	0.15	0.86	0.13	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
July	0.15	0.86	0.13	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
August	0.15	0.86	0.13	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
September	0.15	0.86	0.13	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Table G3. Aircraft-Ground MRM Probability Table for FY00.

	$\hat{\lambda}_t$	0	1	2	3	4	5	6	7	8	9	10
October	1.57	0.21	0.33	0.26	0.13	0.05	0.02	0.00	0.00	0.00	0.00	0.00
November	1.56	0.21	0.33	0.26	0.13	0.05	0.02	0.00	0.00	0.00	0.00	0.00
December	1.55	0.21	0.33	0.25	0.13	0.05	0.02	0.00	0.00	0.00	0.00	0.00
January	1.54	0.21	0.33	0.25	0.13	0.05	0.02	0.00	0.00	0.00	0.00	0.00
February	1.52	0.22	0.33	0.25	0.13	0.05	0.01	0.00	0.00	0.00	0.00	0.00
March	1.51	0.22	0.33	0.25	0.13	0.05	0.01	0.00	0.00	0.00	0.00	0.00
April	1.50	0.22	0.33	0.25	0.13	0.05	0.01	0.00	0.00	0.00	0.00	0.00
May	1.49	0.23	0.34	0.25	0.12	0.05	0.01	0.00	0.00	0.00	0.00	0.00
June	1.48	0.23	0.34	0.25	0.12	0.05	0.01	0.00	0.00	0.00	0.00	0.00
July	1.46	0.23	0.34	0.25	0.12	0.04	0.01	0.00	0.00	0.00	0.00	0.00
August	1.45	0.23	0.34	0.25	0.12	0.04	0.01	0.00	0.00	0.00	0.00	0.00
September	1.44	0.24	0.34	0.25	0.12	0.04	0.01	0.00	0.00	0.00	0.00	0.00

Table G4. Class A MRM Probability Table for FY00.

	$\hat{\lambda}_t$	0	1	2	3	4	5	6	7	8	9	10
October	0.31	0.73	0.23	0.04	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
November	0.31	0.74	0.22	0.04	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
December	0.30	0.74	0.22	0.04	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
January	0.30	0.74	0.22	0.04	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
February	0.30	0.74	0.22	0.04	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
March	0.29	0.75	0.22	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
April	0.29	0.75	0.22	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
May	0.29	0.75	0.22	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
June	0.28	0.75	0.22	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
July	0.28	0.76	0.21	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
August	0.28	0.76	0.21	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
September	0.28	0.76	0.21	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Table G5. Class B MRM Probability Table for FY00.

	$\hat{\lambda}_t$	0	1	2	3	4	5	6	7	8	9	10
October	0.37	0.69	0.25	0.05	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00
November	0.37	0.69	0.25	0.05	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00
December	0.37	0.69	0.25	0.05	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00
January	0.36	0.70	0.25	0.04	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00
February	0.36	0.70	0.25	0.04	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00
March	0.36	0.70	0.25	0.04	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00
April	0.36	0.70	0.25	0.04	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00
May	0.35	0.70	0.25	0.04	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00
June	0.35	0.70	0.25	0.04	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00
July	0.35	0.71	0.24	0.04	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00
August	0.35	0.71	0.24	0.04	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00
September	0.34	0.71	0.24	0.04	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Table G6. Class C MRM Probability Table for FY00.

	$\hat{\lambda}_t$	0	1	2	3	4	5	6	7	8	9	10
October	2.35	0.10	0.22	0.26	0.21	0.12	0.06	0.02	0.01	0.00	0.00	0.00
November	2.33	0.10	0.23	0.26	0.21	0.12	0.06	0.02	0.01	0.00	0.00	0.00
December	2.31	0.10	0.23	0.26	0.20	0.12	0.05	0.02	0.01	0.00	0.00	0.00
January	2.30	0.10	0.23	0.27	0.20	0.12	0.05	0.02	0.01	0.00	0.00	0.00
February	2.28	0.10	0.23	0.27	0.20	0.12	0.05	0.02	0.01	0.00	0.00	0.00
March	2.26	0.10	0.24	0.27	0.20	0.11	0.05	0.02	0.01	0.00	0.00	0.00
April	2.25	0.11	0.24	0.27	0.20	0.11	0.05	0.02	0.01	0.00	0.00	0.00
May	2.23	0.11	0.24	0.27	0.20	0.11	0.05	0.02	0.01	0.00	0.00	0.00
June	2.21	0.11	0.24	0.27	0.20	0.11	0.05	0.02	0.01	0.00	0.00	0.00
July	2.20	0.11	0.24	0.27	0.20	0.11	0.05	0.02	0.01	0.00	0.00	0.00
August	2.18	0.11	0.25	0.27	0.20	0.11	0.05	0.02	0.01	0.00	0.00	0.00
September	2.16	0.12	0.25	0.27	0.19	0.10	0.05	0.02	0.01	0.00	0.00	0.00

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